Technical Note N-1133

SPECIALIZED ANCHORS FOR THE DEEP SEA - PROGRESS SUMMARY

By

J. E. Smith, R. M. Beard, and R. J. Taylor

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ABSTRACT

Five anchor design concepts have been explored in conjunction with the program to develop an improved deep sea mooring capability. The knowledge gained from study of these anchor concepts, (1) "Free-fall", (2) "Pulse-jet", (3) "Explosive", (4) "Padlock", and (5) "Vibratory", are summarized in this report.

The vibratory anchor is currently the center of the deep sea anchoring development effort. A first generation design has demonstrated the concept to be feasible. Tests have shown that improvements are required for the vibratory anchor. An analytical study has been performed to assist in optimizing a second generation design. Improvements incorporated in the second generation design will be based on information from tests of the first design and the analytical study. The improved design will be tested in a range of seafloor sediment types and water depths to rate its capabilities and establish its reliability.

CONTENTS

INTRODUCTION

Background

Anchors and anchorage systems are an important but neglected area of development in the greatly expanding field of ocean exploration and exploitation. There are requirements for sophisticated structures and instrument arrays plus other constructions to be positively and reliably secured in position on and under the sea in depths and locations not normally associated with anchoring. Yet, while intense effort is being expended on design and development of the constructions, attempts are made to hold them in position with dead weights and/or with conventional anchors ill-suited to the unusual demands put upon them.

The U. S. Naval Facilities Engineering Command is sponsoring a program at the U. S. Naval Civil Engineering Laboratory, Port Hueneme, California, concerned with improving anchoring capability for mooring Navy equipment in the deep sea. Early objectives are to obtain a functional anchor design with a working holding capacity in the range of 25,000 to 50,000 pounds and operational in depths to 6,000 feet in seafloor sediments. An anchor with this capacity would provide a practical advantage over use of dead weights and conventional anchors. The 6,000-foot depth affords a practical anchoring capability throughout all continental shelf areas plus many strategic ocean areas beyond the continental shelves, e.g., sea mounts. Later objectives include anchoring capacities in the 100,000 to 300,000 pound range and an operational depth capability to 20,000 feet.

At this stage in the program, a vibratory anchor design that appears to approach the early objectives of anchoring in soft sediments has been achieved. Also, valuable knowledge on other anchor designs and techniques has been gained. This report traces the history of the program and describes the present status of the vibratory anchor.

Requirements

There is a wide variety of structures and constructions for which deep ocean anchorage requirements exist. Mooring configurations to meet these requirements may be placed in four major categories: surface-single leg; surface-multi-leg; subsurface-single leg; subsurface-multi-leg. In addition, new areas of construction effort involve bottom rest structures for which the term anchorage may properly be applied to refer to the means of supporting and restraining the structures.

The types of structures for which deep water moors are needed include oceanographic data buoy stations, surface and subsurface instrument arrays, ships, submarines beneath the surface, and manned or unmanned sea platforms. As yet, it is not valid to label any deep sea moor as a typical design. Some significant deep sea moors have been accomplished that illustrate both the requirements and the problems. Among these are the Tongue of the Ocean II (TOTO II) moor for large surface vessels, Figure 1, Naval Oceanographic Meteorological Automatic Device (NOMAD) anchor system, Figure 2, and the U. S. Coast and Geodetic Survey, Undersea Stabilized Platform, Figure 3, (Smith, 1965). Several underwater instrument array anchoring methods are depicted in Figures 4 and 5. It is noteworthy with respect to problems of deep sea moors that a moor system similar to the undersea stabilized platform design that was installed in 4,000 feet was attempted in water 18,000 feet deep. It was unsuccessful and a major difficulty pertained to lack of adequate anchors specially adapted for use in the deep sea (Interstate Electronics Corporation, 1970).

Modified Anchor Criteria

Conventional anchors have evolved through the ages into efficient implements to meet holding requirements under many operational conditions. There is much diversification in sizes, shapes, and arrangement of components of conventional anchors. However, all conventional anchors share certain characteristics that can serve to good advantage in meeting conditions for which they are designed but which are detrimental in deep ocean applications. They must be dragged in order to embed and develop rated holding capacity. The dragging force must be applied parallel or near parallel to the seafloor. They then are able to resist maximum forces only from the direction in which they were dragged. Forces from other directions and/or uplift forces greatly reduce their holding capability. One other limitation is that the performance of conventional anchors in hard seafloors is erratic and unreliable. In such conditions, they do not embed but depend on holding by falling into a crevice or by snagging on a protrusion or outcropping.

These characteristics demonstrate the unsatisfactory nature of conventional anchors for deep water applications. Large scopes of line and other connective gear are required first to apply the forces parallel to the seafloor to effect embedment and second to maintain the parallel force direction during use. Attendant surface operational and coordination problems in handling the immense amounts of line and in maintaining correct position and course of work platforms during placement are acute.

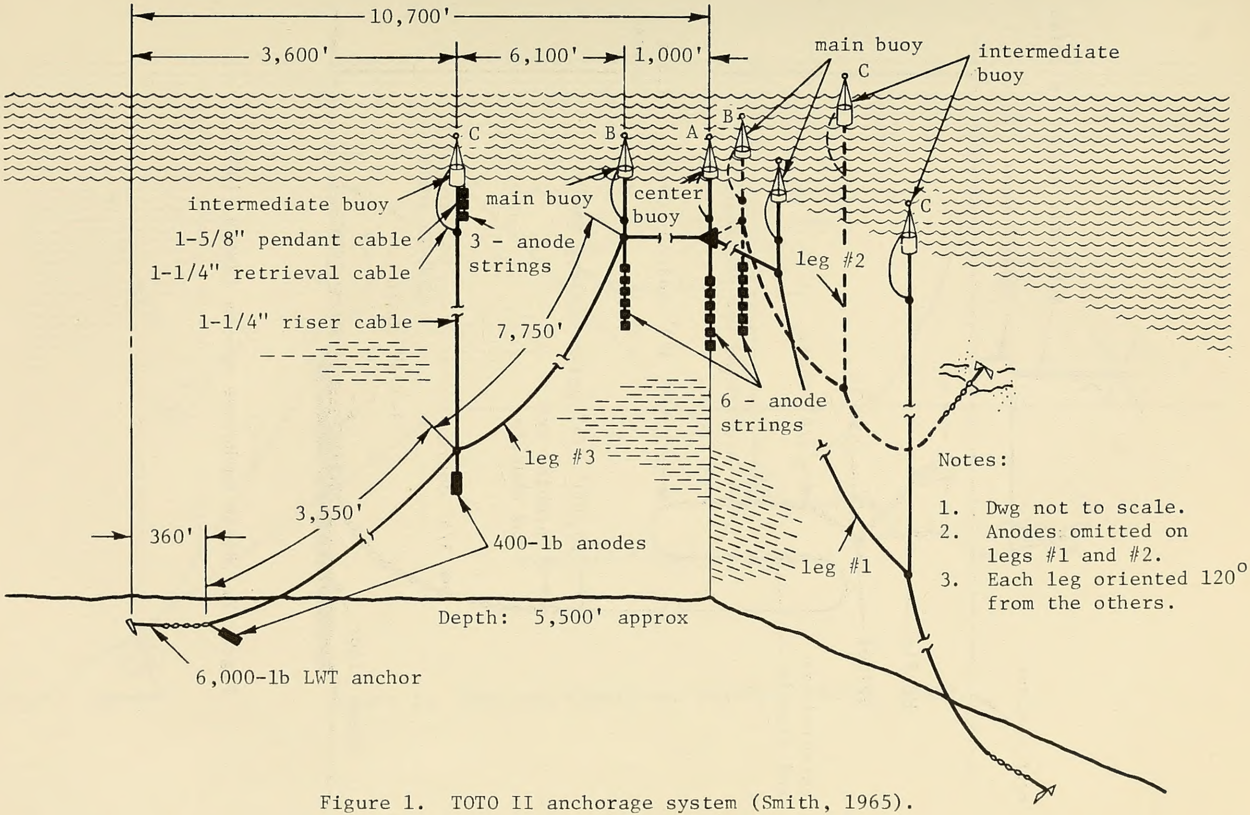

Figure 1. TOTO II anchorage system (Smith, 1965).

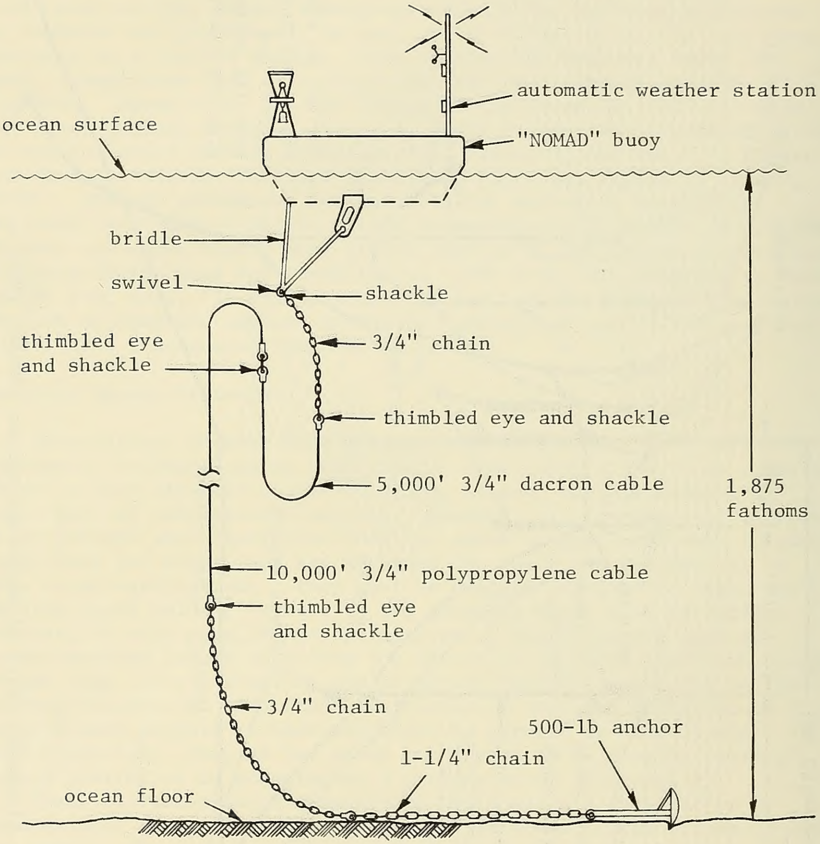

Figure 2. NOMAD anchorage system (Smith, 1965).

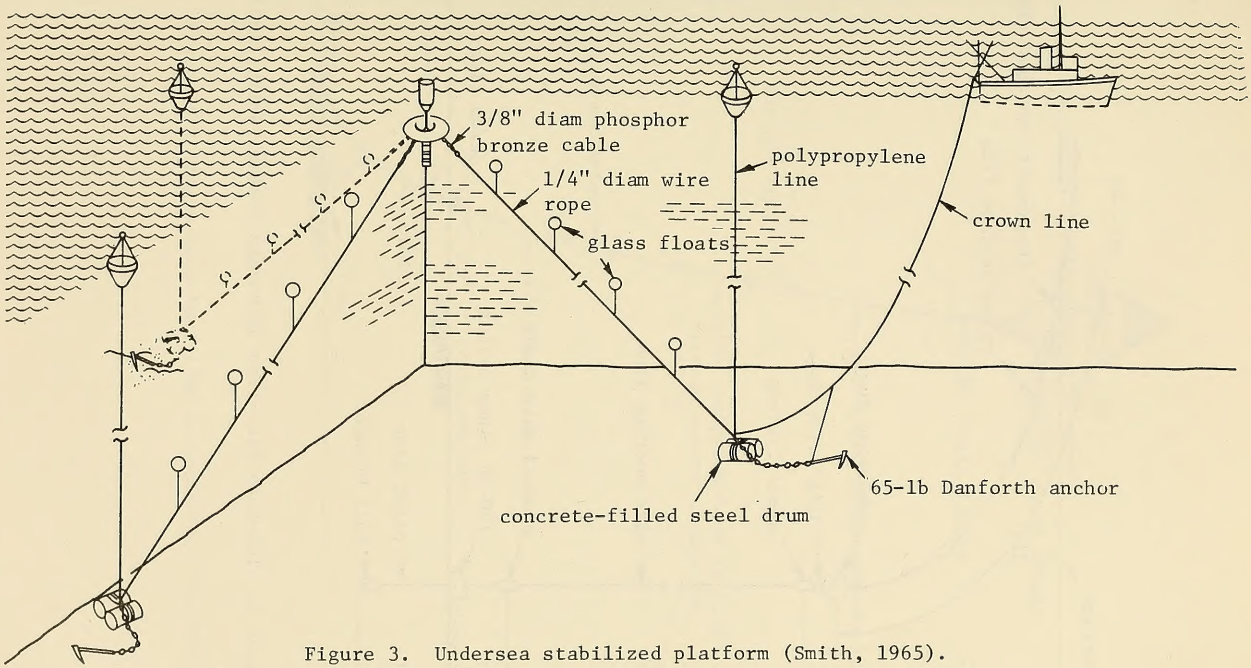

Figure 3. Undersea stabilized platform (Smith, 1965).

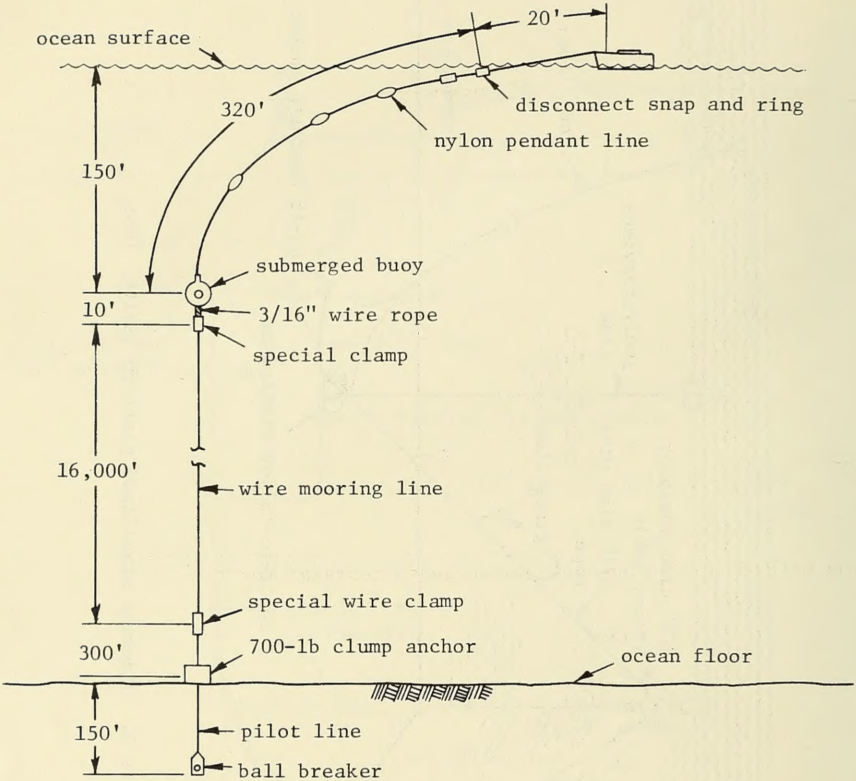

Figure 4. Two-buoy taut-line anchorage system (Smith, 1965).

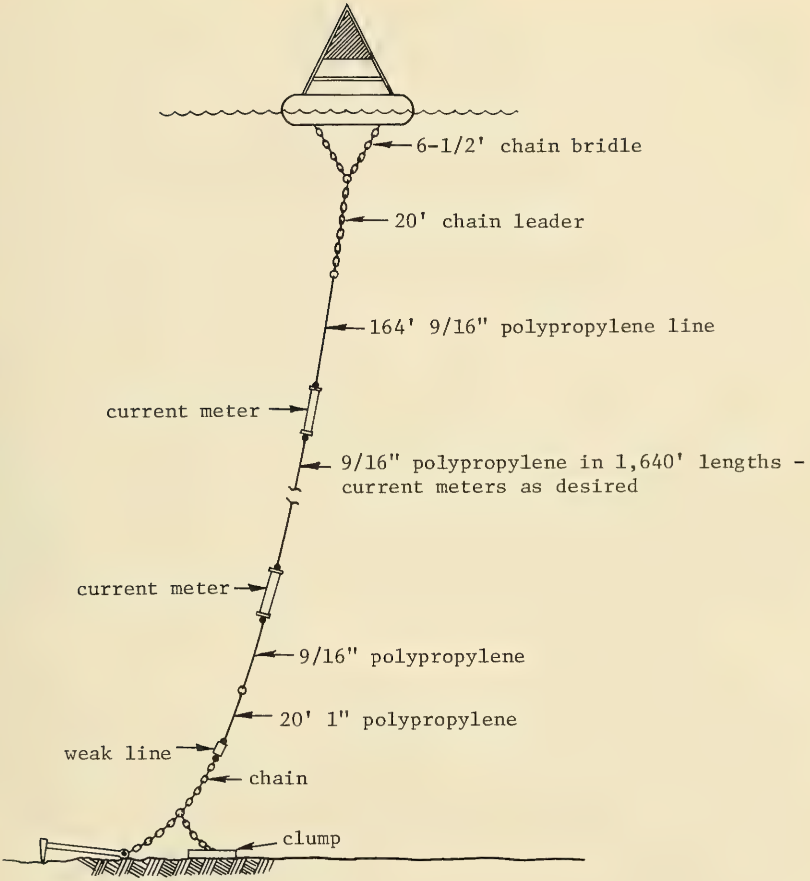

Figure 5. Single-buoy taut-line anchorage system (Smith, 1965).

Special anchor designs are needed to overcome these deficiencies. Key criteria for a deep ocean anchor are that it be capable of directly embedding into the seafloor without being dragged and capable of resisting uplift as well as lateral loads from all directions without reducing its holding performance. Other desirable attributes are that the anchor be lightweight, well configured for handling and lowering, simple in operation, economical of materials and construction, self controllable or controllable from the surface, and readily adaptable to different appurtenances and connective gear.

In addition to the anchor implement, improvements are needed with respect to the connective gear and appurtenances plus the equipment and techniques for handling and installing anchorages in deep water. However, it is judicious first to proceed with improving the single most important feature of a moor, the anchor. Direct embedment of anchors may be achieved by free-fall impetus and/or applied power. Some principal means of powering an anchor into the seafloor are jetting, drilling, vibrating, and propelling with explosives. Considering state-of-the-art of hardware, operational factors for control and placement and cost factors, four anchor concepts have been investigated at the Laboratory that incorporate in one form or another the free-fall, jetting, explosive, and vibratory principles. In addition, a design suitable for supporting bottom rest structures was explored. Substantial knowledge and experience has been gained and a vibratory anchor concept has approached a usable state. Further work on this concept is expected to improve its operation and help define the limits of its capability.

ANCHOR SYSTEMS REVIEW

The "Free-Fall" Anchor

Design Considerations. The "free-fall" concept considered in the Laboratory anchor program is one that utilizes the "free-fall" principle not only to lower the anchor rapidly and efficiently to the seafloor but also to achieve embedment by the free-fall impetus. Results of work with this concept were reported (Smith, 1966a). Pertinent facts are presented here to place the "free-fall" anchor developments in proper perspective relative to the further program. The prospects of a "free-fall" anchor that would accomplish the functions envisioned were intriguing. Though holding capacities would be limited to moderate values, many urgent requirements for anchoring relatively small structures could be satisfied. Quick, easy, more accurate placement of anchors could be achieved and better holding power efficiency as measured by holding power-to-weight ratio could be attained. Holding capacities of 15,000-25,000 pounds were considered adequate values to meet these requirements.

Two problems are intrinsic to the "free-fall" anchor principle: (1) the means of handling the connective cable or line as the anchor falls to the seafloor and (2) the means of embedding the anchor a sufficient distance into the seafloor to enable the development of reasonable holding capacity. The first problem concerns the connective cable. An anchor in the seafloor is of little use if there is no method to connect to and utilize its holding ability. In deep water, the only expedient approach is to keep a line attached to the anchor as it is being lowered to the seafloor. If the line is permitted to payout at the surface and trail the anchor to the seafloor, major difficulties are encountered. Lines moving with high velocity on the deck of a work platform at sea are hazardous. Long lengths of line may become a drag factor slowing the anchor's descent, or conceivably in some cases, portions of a moving line could overtake the anchor and entangle with it. Whatever the developments on the way down, braking the line would be difficult once the anchor reached the seafloor and massive entanglements would result.

An alternate solution is to attach all the cable necessary to reach the seafloor to the anchor and to launch it with the anchor while holding the bitter end at the surface. This procedure also has disadvantages. The approximate length of the cable required must be predetermined and packaged to accommodate the water depth. Long lengths of cable form a bulky package that limit the size and length of cable practicable to use. Nevertheless, for smaller sizes of line and operation to intermediate depths, i.e., to 6,000 feet, advantages of this payout approach outweigh the surface payout system.

A. C. Electronics Corporation (formally Defense Research Laboratories) Goleta, California has developed two techniques of packaging cables for payout from free-falling weights in water, a coiled pack and a random pack. The coiled method results in a compact package but requires a twist in the cable for each layer and much energy is consequently stored in the resulting bale. Even with the twist, only a portion of the 360 degree turn in the cable (about 60 percent) can be compensated. Thus, additional rotation of the cable must be accommodated once payout is complete. The random coil method does not require a preset twist for each cable layer but results in a much bulkier package for a given length of cable.

The coiled cable system for the bale was selected for use in the free-fall anchor design because of its compactness. Work then proceeded to obtain a practicable design to realize the potential advantages of the free-fall anchor concept.

The second problem concerns anchor embedment. Flukes are the primary components of an anchor that penetrate then mobilize the seafloor strata material to resist applied loads. Conventional anchors are so constructed that their flukes embed as a result of an applied force comparable in direction to that which they resist when in service.

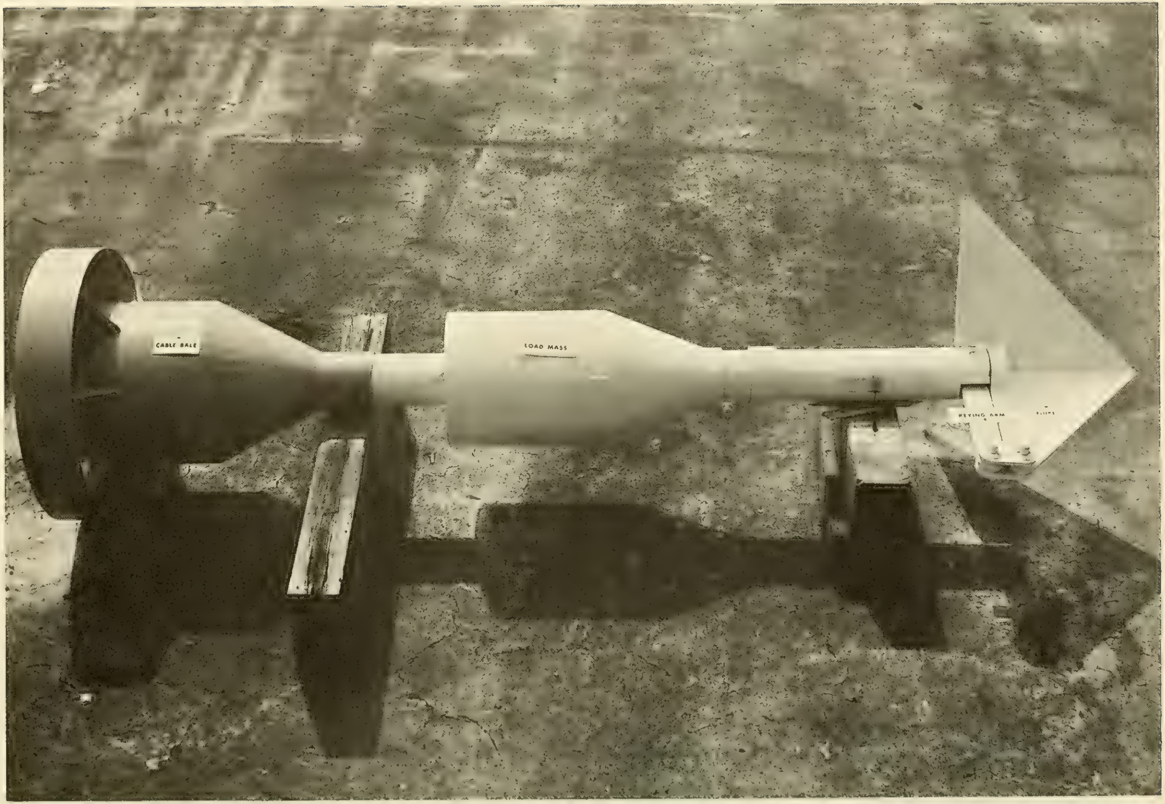

Figure 6. Free-fall embedment anchor.

Thus, in-service forces tend to embed them deeper. In contrast, special anchors such as the "free-fall" must attain embedment of their flukes by an applied force opposite to that which they ultimately must resist when in service. Thus, in-service forces tend to extract them. Consequently, it is important that the flukes of the free-fall anchor penetrate as deeply as possible into the seafloor during placement. To accomplish this penetration, the anchor and flukes must present a minimum resistance to the soil. Following embedment, it is essential that the flukes change to a position offering maximum resistance to movement through the soil. Further, they should change to this position with the least possible vertical displacement because the deepest, least disturbed material reached by the flukes with few exceptions will afford greater resistance to in-service loads than the overlying sediments the flukes have passed through.

Description and Results. A free-fall anchor design within the context of task goals was achieved. Prototype and model scale testing were conducted. After minor modifications to the initial design, the NCEL free-fall anchor, Figure 6, evolved. It is a steel construction in the general shape of an arrow and consists of three basic components; a fluke assembly at the arrow-tip end, a heavy steel shank in the central portion, and a barrel shaped bale with protuding fins at the trailing end. The design incorporated the coil payout cable system and a unique fluke design to gain the maximum potential of the free-fall anchor principle.

As reported (Smith, 1966a) the free-fall anchor as a practical, usable deep sea anchor that could be free-dropped and, by its own impetus, embed into the seafloor and develop a holding capacity of sufficient amount to warrant its use in place of dead weights was not obtained. The primary reason was that the size and configuration of the anchor necessary to accommodate the cable bale combined with the size and shape of flukes necessary for reasonable holding power were not compatible with attaining the velocity needed to obtain adequate embedment. For example, it was determined that even with the maximum theoretical velocity attainable by free-fall (about 35 fps) a holding capacity to weight ratio of only 3 or 4 to 1 could be obtained. A minimum ratio of 7-to-1 is considered necessary for the free-fall anchor to be feasible.

Despite failure to achieve the idealized goal for a free-fall anchor, significant contributions toward development of improved, direct embedment deep sea anchors were realized. The cable payout system for deploying anchors in the deep sea works, and has practical application within certain operational, size, and depth limitations. Knowledge and experience gained can be used to good advantage in utilizing this system in deploying future deep sea anchors. More important is the revolutionary fluke incorporated into the design of the free-fall anchor. This fluke proved highly efficient and is adaptable to other types of direct embedment anchors. A more detailed description of the new fluke is given in the section dealing with the vibratory anchor.

Explosive Embedment Anchors

History. Some means other than or in addition to free-fall impetus is essential to embed anchors deep enough to gain greater holding capabilities than can be expected of free-fall anchors. Accordingly, the program to develop a better deep sea anchoring capability has included investigation of anchors with power features to achieve embedment. One such type is referred to as explosive anchors.

Explosive anchors utilize a propellant charge to impart high velocity to the anchor which by virtue of its kinetic energy then penetrates into the seafloor. Initial development work on explosive anchors began about 1959. Two private industrial concerns provided the initiative to conduct the early work. Shortly thereafter, the U. S. Army Mobility Equipment Research and Development Center (MERDC) formerly U. S. Army Engineering Research and Development Laboratory (ERDL) at Fort Belvoir, Virginia sponsored the development of one of the two concepts to meet requirements for special offshore mooring capability for anchors in amphibious operations. The Naval Civil Engineering Laboratory (NCEL) provided support facilities for some of the early testing sponsored by MERDC.

The investigation of explosive anchors for deep ocean application was undertaken at NCEL in 1965. At that time, two commercial anchors emanating from the efforts of the two private concerns were being marketed as off-the-shelf items. Also, work on the anchor design MERDC was sponsoring under contract had been taken in-house and an anchor similar to one of the commercial items had been achieved. NCEL's investigation with explosive anchors has included tests of the two commercial anchors followed by tests of the MERDC anchor. Results of tests of the commercial anchors were reported by Smith (1966b). Development work on explosive anchors of MERDC was reported by Christians (1967). Pertinent facts about the commercial and MERDC anchors are described here to place the explosive anchor developments in perspective relative to the total ongoing deep ocean anchoring program.

Description. The explosive anchor designs tested at the Laboratory are shown in Figures 7, 8, and 9. Though they differ in shape and/or size, each is comprised of two major components; an anchor-projectile and a gun-reactor. The anchor-projectile is that portion of the assembly that is propelled into the seafloor. One style of anchor-projectile is a shield shape that penetrates the seafloor edgewise, then "keys" over to a position that presents a maximum area to resist pullout when load is applied. This style is evident in Figures 8 and 9. The second style of anchor-projectile consists of a shank that contains two flukes. This anchor-projectile enters the seafloor endwise. When loads are applied, the flukes extend outward to acquire increased resistance to extraction. This style of anchor-projectile is shown in Figure 7. Both styles of anchor-projectile have a separate portion called a piston that inserts into the gun-reactor and is expelled when the propellant is ignited.

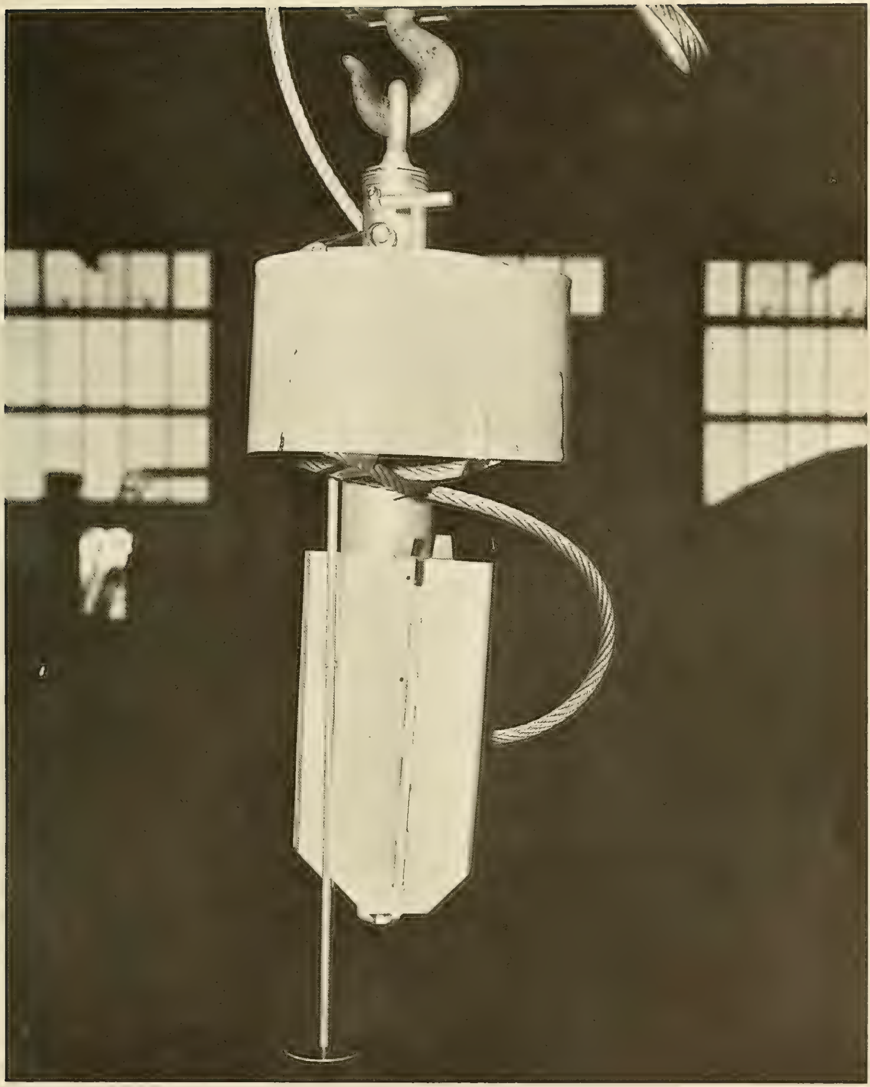

Figure 7. Hove II explosive embedment anchor.

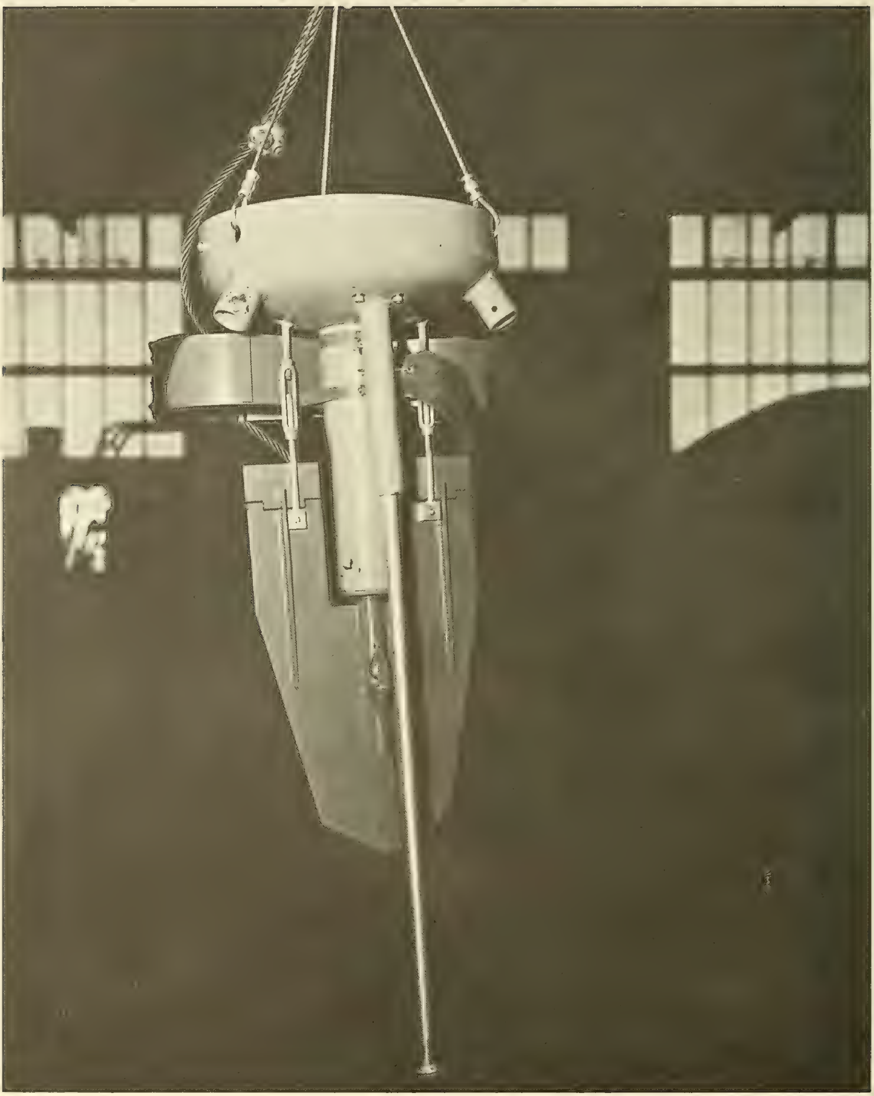

Figure 8. SEASTAPLE explosive embedment anchor (Smith, 1965).

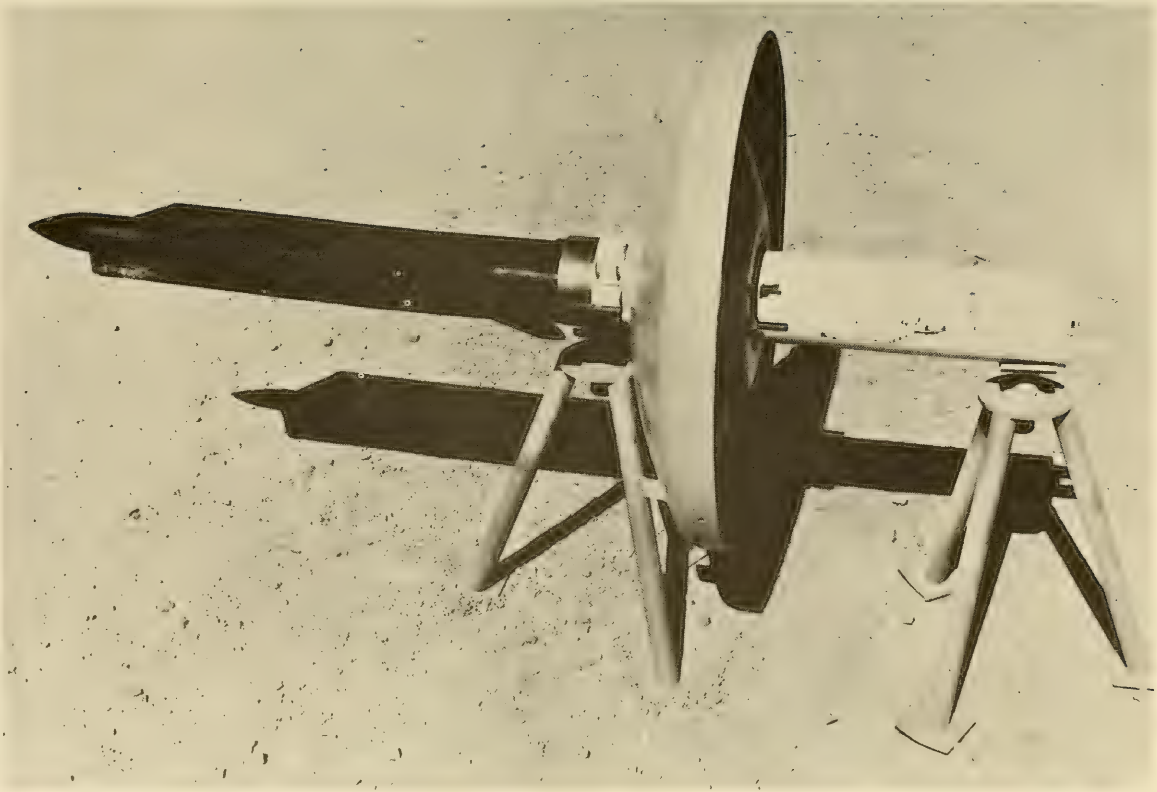

Figure 9. MERDC explosive anchor, 50,000 pound capacity.

The gun-reactor consists of a gun barrel and a disc- or cone-shaped part that serves to help counteract the reaction force, generated as the anchor-projectile is accelerated away from the gun-reactor. A removable breech block at the breech end of the gun-reactor provides the means for inserting and containing the propellant charge. The gun-reactor can be reused to fire a succession of anchor-projectiles. Its reuse is contingent upon two factors. First, it must be retrieved. Retrieval is not a difficult problem in shallow water but is a major consideration in deep water. Second, it must be reconditioned after a specified number of discharges due to the severe shocks it experiences at each recoil.

Another important feature of explosive anchors is the wire rope pendant which must be attached to and trail the anchor-projectile into the seafloor. The pendant must be packaged or otherwise arranged in a manner that will permit it to payout at high velocity without entanglements, kinks, or other damaging effects. The pendants for the three designs are accommodated in two ways. For the two commercial anchors, which are small by comparison to the MERDC anchor, the pendants are packaged in a figure 8 so that they payout without a twist and without damage, Figures 10 and 11. For the larger MERDC anchor, the pendant is faked on a board fastened to the anchor assembly, Figure 12.

Two methods are employed to discharge the explosive anchors; one is by contact with the seafloor and the other is by signal control from the surface. For the contact method, a rod extends below the main anchor assembly and contacts the seafloor as the assembly is lowered. Upon contact, it mechanically actuates an electrical or mechanical firing system. Electrical or mechanical actuations may be used on any of the designs. For the signal control method, the anchor with an attached tripod support framework is lowered to the seafloor. Then with the anchor supported and oriented on the seafloor by the tripod, it is discharged using an electrical cable extending to the surface. During work by NCEL with the MERDC anchor, a refinement of the contact method was developed whereby discharge of the anchor occurred a preset time after touchdown. This method improved operations procedures and safety.

Tests and Results. A summary of deep water tests and results with the explosive anchor designs is presented in Table 1. The tests demonstrated that explosive anchors can function in deep water. The tests also served to identify major problem areas associated with the use of explosive anchors in deep water. Chief problems concern:

1. Preparing and regulating the firing process;

2. Orienting the anchor properly with respect to the seafloor prior to discharge;

3. Monitoring and establishing control over the penetration process; and

4. Retrieving the expensive, reusable gun-reactor portion.

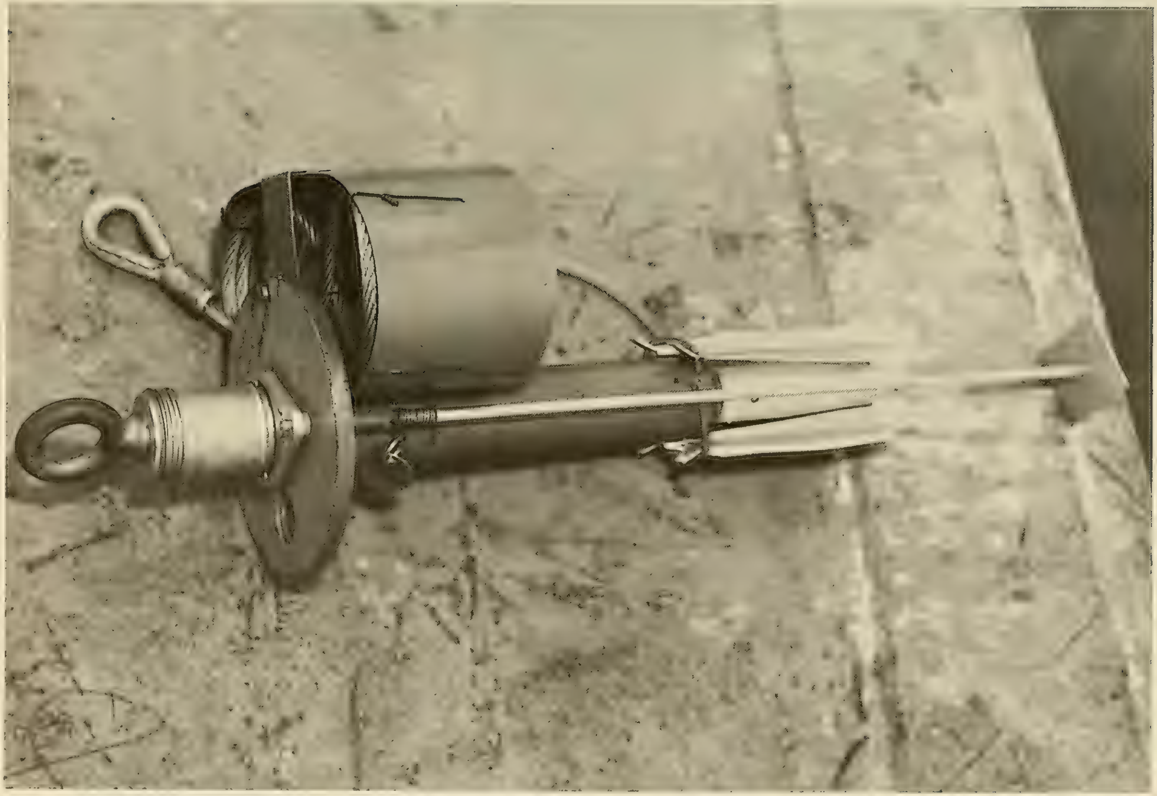

Figure 10. Hove II, showing bail and cable.

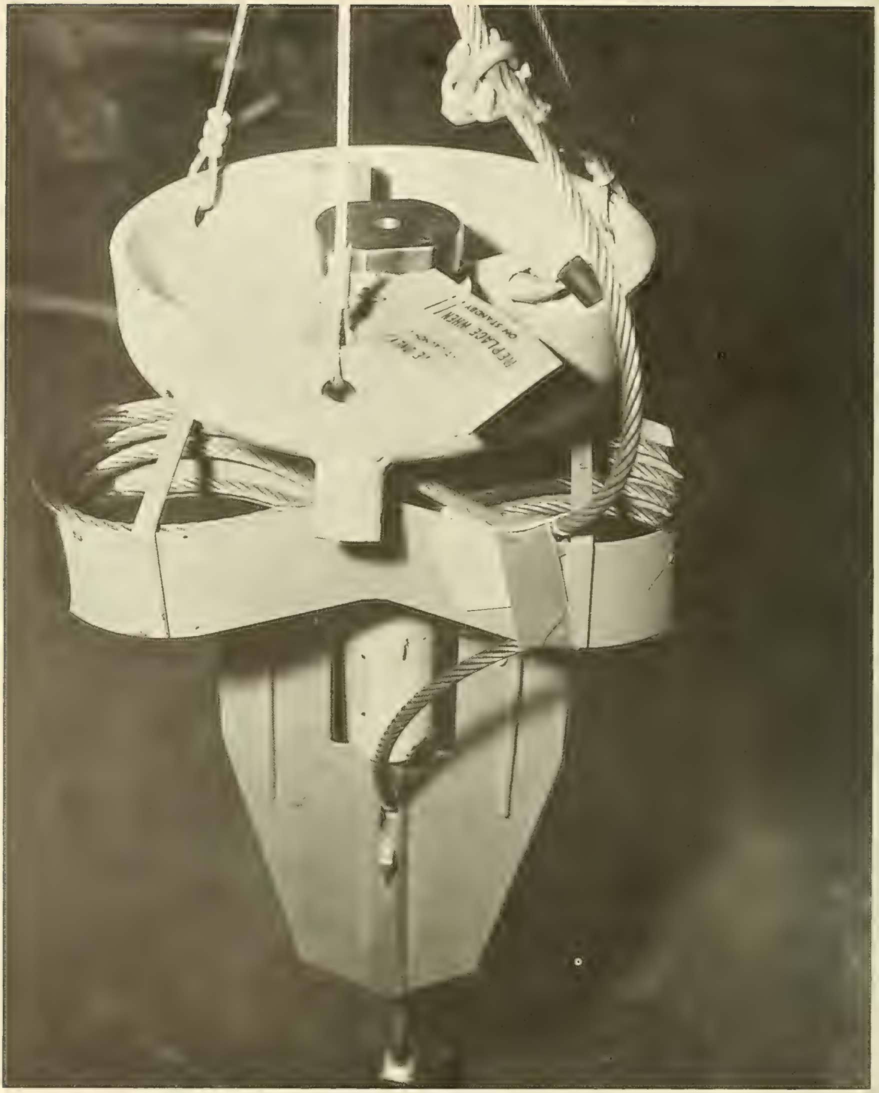

Figure 11. SEASTAPLE, showing bail and cable.

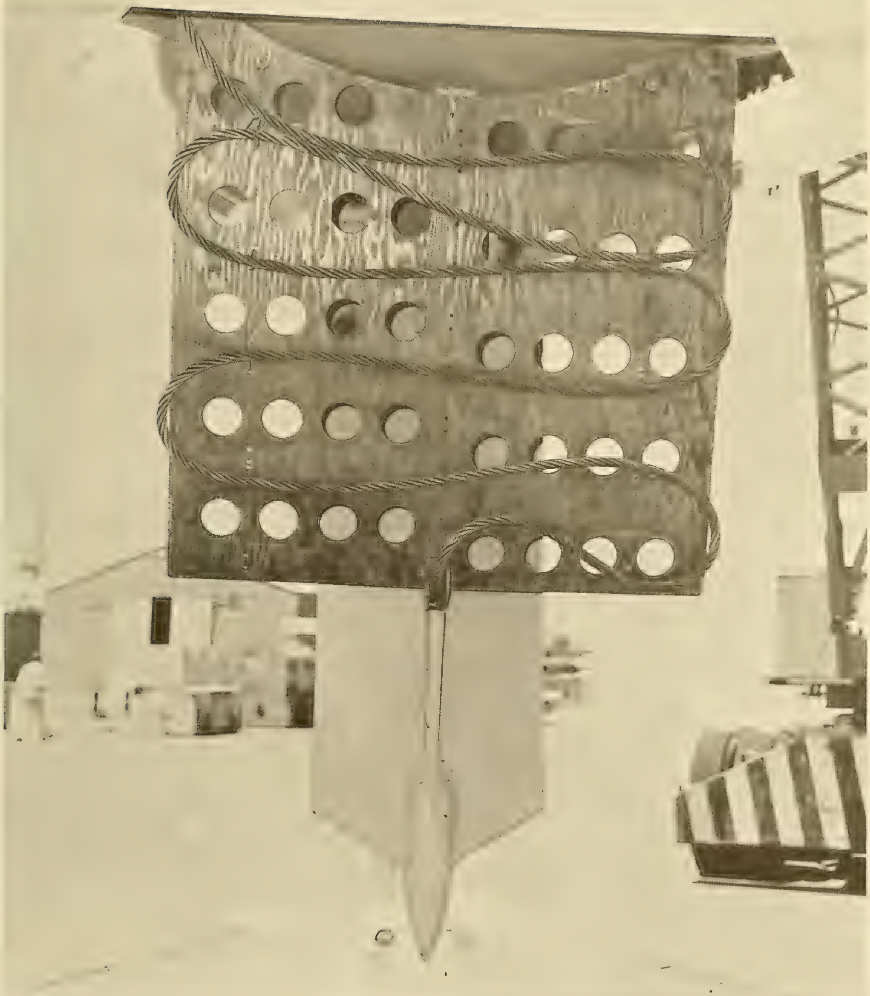

Figure 12. MERDC anchor, showing faked cable.

Table 1. Explosive Anchor test results.

Anchor	Seafloor Type	Water Depth (ft)	Maximum Load (Percent of Rated Capacity)	Comments
Seastaple (5-kip)	Sand	45	---	Malfunctioned
		45	---	Malfunctioned
		45	300	Pendant broke--anchor lost
		58	150	Pendant broke--anchor lost
		58	60	Anchor retrieved--damaged
		58	---	Malfunctioned
	Mud	102	100	Anchor retrieved--damaged
		102	---	Malfunctioned
		70	---	Malfunctioned
		70	70	Anchor retrieved--damaged
		63	180	Anchor did not discharge on first lowering. Anchor retrieved--damaged
		75	130	Anchor retrieved--damaged
Hove II (5-kip)	Sand	*45	107 of 10k	Anchor retrieved--flukes missing
		65	---	Malfunctioned
		65	---	Malfunctioned
		65	140	Anchor retrieved--one fluke missing
		54	---	Malfunctioned
	Mud	102	70	Anchor retrieved--undamaged
		102	---	Malfunctioned
		102	---	Malfunctioned
		102	---	Malfunctioned
Seastaple (5-kip)	Sand	1,350	---	Lowering lines became entangled
		2,250	45	Anchor retrieved--undamaged
	Mud	1,180	---	Malfunctioned
		1,180	50	Anchor retrieved--undamaged
		1,860	30	Anchor retrieved--undamaged
		5,970	---	Malfunctioned
		6,000	40	Anchor retrieved--damaged
Hove II (10-kip)	Sand	2,850	---	Malfunctioned
	Mud	1,100	60	Anchor retrieved--flukes bent
		1,860	---	Malfunctioned
MERDC (50-kip)	Sand	1,260	45	Pendant broke--anchor lost
	Mud	1,400	20	Anchor retrieved--undamaged

* The 10-kip Hove II was used in this test.

Prospective advantages of explosive anchors for deep water use outweigh the disadvantages. However, work with them was suspended in favor of the vibratory anchor design when it was conceived. The vibratory anchor appeared to possess more favorable operational and control characteristics.

Pulse-jet Anchor Concept

Background. The pulse-jet anchor concept came to attention during the investigation of the explosive anchors. It became evident during testing of the explosive anchors that a power action extending throughout the embedment phase of anchor placement would be advantageous by more readily accommodating the variable resistance to penetration offered by seafloors comprised of hard and soft sediments. The pulse-jet principle offered a potential that would achieve the goal of extending the time during which power is applied to embed the anchor. The concept was investigated under contract by Sea Space Systems, Incorporated. The Contractor was to design and fabricate two experimental models and conduct developmental testing. Then two prototype models were to be delivered for Government testing.

The concept proved to be not feasible and the contract was reduced in scope to include a report on the effort (Lair, 1967). Salient facts about the pulse-jet anchor are presented here to help cover all aspects of the deep ocean anchor development program.

Description. The pulse-jet anchor as envisaged is comprised of two principal parts called a Mass Drag Reactor, Figure 13, and a Ballistic Embedding Anchor, Figure 14. For application, the Ballistic Embedding Anchor is meshed with the Mass Drag Reactor. The resulting assembly is lowered to the seafloor. On contact, a propellent in the Mass Drag Reactor gives the Ballistic Embedding Anchor an impetus to embed at least its own length into the seafloor. To this point, the principle is similar to that for other explosive anchors. The Ballistic Embedding Anchor consists of three main components: a main structural body, an inner inertial reciprocator which executes a short stroke with respect to the structural body, and an innermost free-sliding valve which executes a shorter stroke than the reciprocator and governs the stroke of the latter. As it is expelled from the Mass Drag Reactor, the anchor comes to contain a charge of expulsion gages that is trapped and sealed into the anchor at about 20,000 psi. Beyond this point the principle differs from that of other explosive anchors. This charge of gas is then distributed by the valve to drive the reciprocator up and down and ultimately is exhausted forward from the anchor nose to break up the seafloor in front of the advancing anchor. The embedment phase ceases when the gas pressure equals that of the ambient sea. Then as load is applied to the anchor, it keys over to a position of maximum resistance.

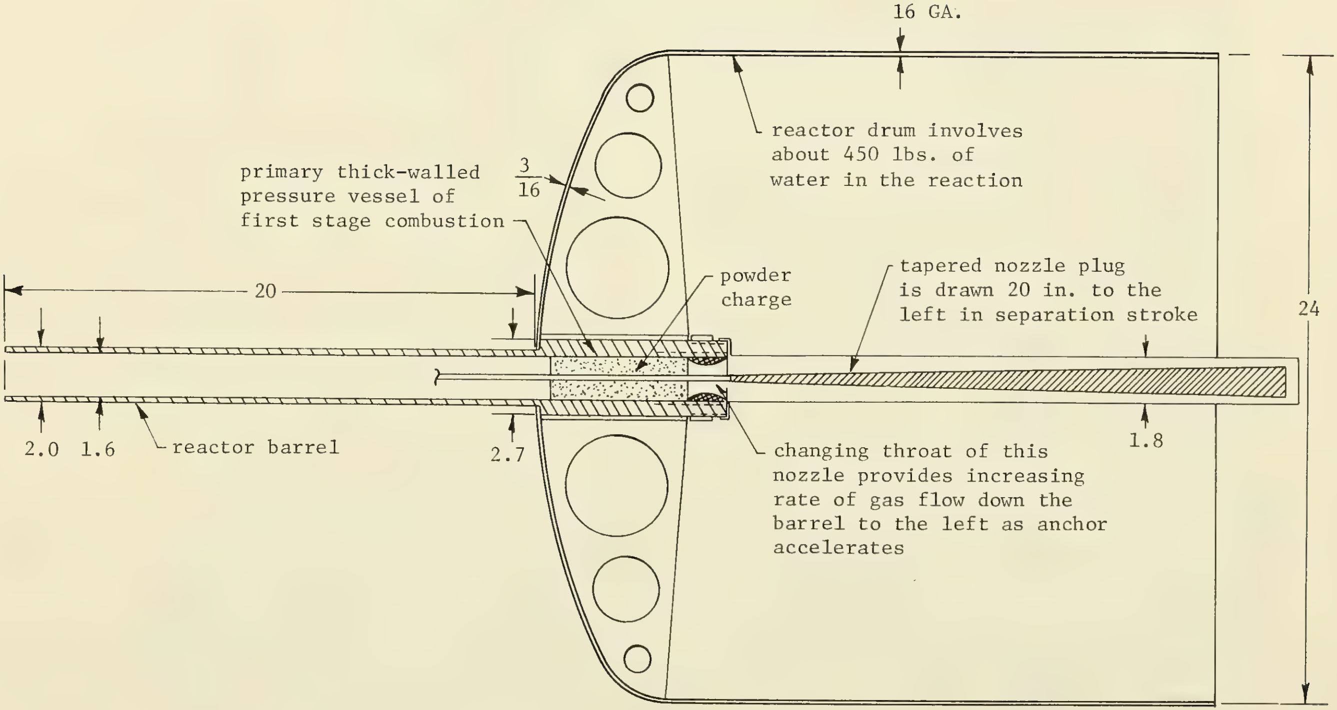

Figure 13. Mass drag reactor of the pulse-jet anchor system (Lair, 1967).

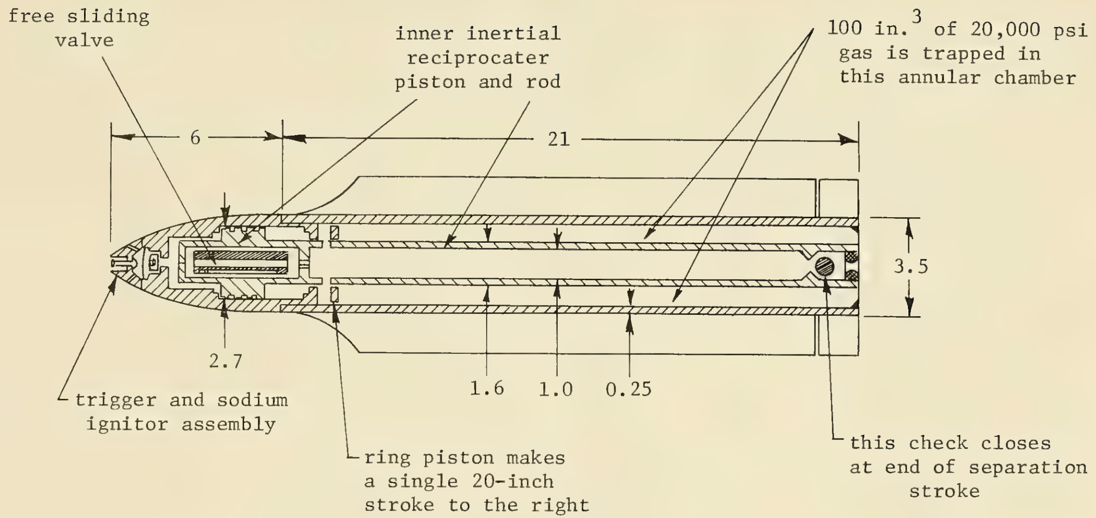

Figure 14. Ballistic embedding anchor of the pulse-jet anchor system (Lair, 1967).

Results and Conclusions. The Contractor was unable to achieve an experimental model of the design envisaged. Two ideas were reported as being too optimistic. The first related to the reciprocating machine. Sliding seals could not be made to function satisfactorily at the high temperatures and pressures encountered in the design. The second pertained to determining the critical relationship between the internal mechanics of the anchor and the soil mechanics of the seafloor. Extensive and expensive developmental testing was indicated for both problem areas with no assurance of success.

Two ideas were reported to have stood up under study and evaluation. The first was the multi-phase release of energy concept. The second was the forward jetting of exhaust gases to assist and regulate anchor embedment.

On review of the Contractor's report, it was concluded that the cost to solve the problems for successful development of this concept were too great to warrant further investigation.

The Padlock Anchor

Background. Forthcoming constructions in the oceans at the continental shelf and greater depths demand high capacity fixed-point anchoring systems. Support features are needed that are capable of resisting bearing as well as lateral and uplift forces. Considering these requirements and the developments with explosive anchors at the Laboratory and elsewhere, an approach to a fixed-point anchorage system utilizing lightweight bearing pads and explosive anchors was conceived. An operational feasibility program was initiated at NCEL and proceeded concurrently with the other explosive anchor work underway at NCEL. The objective was to develop and determine the operational feasibility of an anchor system for the deep ocean that would provide a fixed point (resistance to bearing, lateral, and uplift loads) and that could be installed without diver assistance. The scope included the conception, design, fabrication, and evaluation of a self-contained anchor system that employed multiple bearing pads in conjunction with explosive anchors.

The effort, currently suspended, was reported by Dantz (1968). Prominent facts about this concept are set forth here for a complete picture of the anchoring program at NCEL and to convey additional conclusions in light of developments since the work was suspended.

Description. In general, the PADLOCK is a tripod framework constructed of lightweight materials and supported at each leg by articulated round bearing pads. To obtain resistance to uplift, direct embedment anchors are incorporated into the system. The general scheme of the entire system is shown in Figure 15. The bearing pads are connected to the frame with ball-joints to allow the pads to maintain maximum contact with the seafloor, adjusting to contour slopes of about 10 percent. An embedment anchor is housed above each of the bearings.

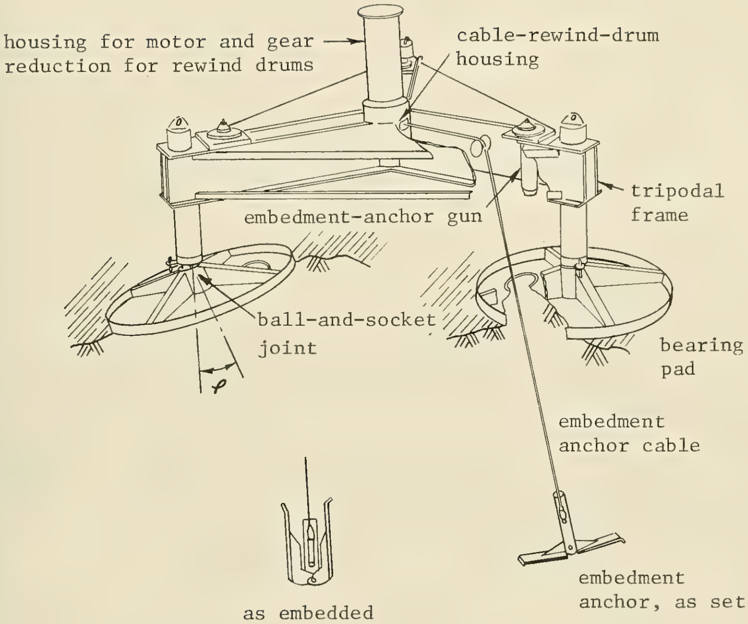

Figure 15. Basic concept of PADLOCK Anchor System (Dantz, 1968).

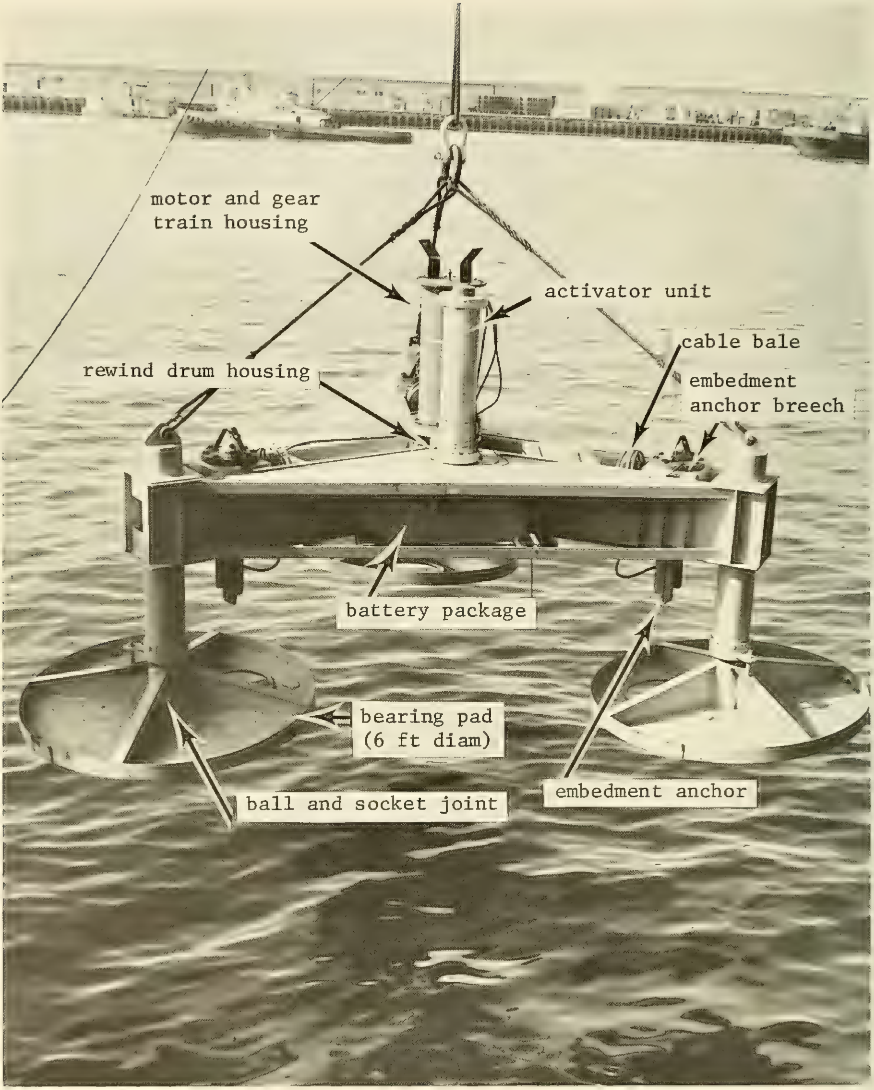

Figure 16. PADLOCK Anchor System developed for test and evaluation (Dantz, 1968).

After the anchors are propelled into the seafloor, they are then set by pretensioning the embedment anchor cables with a rewind mechanism located in a central housing unit at the junction of the arms of the tripod framework. The objective is to clamp the pads to the seafloor by obtaining a firm grip in the seafloor soil with the anchors.

The propellant-actuated (explosive) anchors had demonstrated good prospects for accomplishing the desired anchoring action with a minimum amount of installation equipment. Consequently, this type of anchor was selected to develop the uplift resistance in the PADLOCK design. The particular explosive anchor design chosen was the style that employed two flukes. The commercial anchor of this style was rated as having a nominal 10-kip capacity whereas a 20-kip capacity was desired. Therefore, the manufacturer had to build and deliver a specially enlarged size, Figure 17. The configuration, size, and load-supporting capacities selected were judged sufficient to demonstrate the feasibility of the system.

The PADLOCK prototype fabricated for testing and evaluating is shown in Figure 16. A key feature of the concept is the cable rewind mechanism used to pull up the embedment anchors to a set position. The rewind mechanism consists of three separate cable drivers powered by a common shaft. Each drum wound the cable from one of the embedment anchors and could wind a sufficient length of cable to develop the pretension load for that anchor. Power to the common shaft was from a 24-volt DC motor through a 1356:1 gear reduction as shown in Figure 18. Other features of the concept included: (1) an activator unit to control the sequence of operations of the PADLOCK by acoustic command once it is on the seafloor; (2) an ambient-pressure battery power source; and (3) a shipboard stern roller to assist in the installation of the PADLOCK. This unit is basically an 18-inch diameter sheave with a 12-inch wide shroud designed to permit the passage of lines with shackles, thimbles, and other connective gear. The sheave is connected to two line load-detecting systems. One of these systems is a hydraulic load cell unit with a dial readout and the other is an electric load-cell that may be connected to any electronic readout system. The roller provides a means of handling lines with fittings and a means of constantly monitoring line loads.

Tests and Results. Five shallow water tests were conducted with the PADLOCK in and about Port Hueneme Harbor. Water depths ranged from 18 to 60 feet. The seafloor was primarily hard-packed silty sand. All of the shallow water tests followed essentially the same procedure. Typically, the PADLOCK was transported to sea by a vessel carrying a crane. At the site, the embedment anchors were loaded and armed. Immediately thereafter, the unit was lowered to the seafloor and the anchors were fired. Divers then inspected the system, and the rewind mechanism was started.

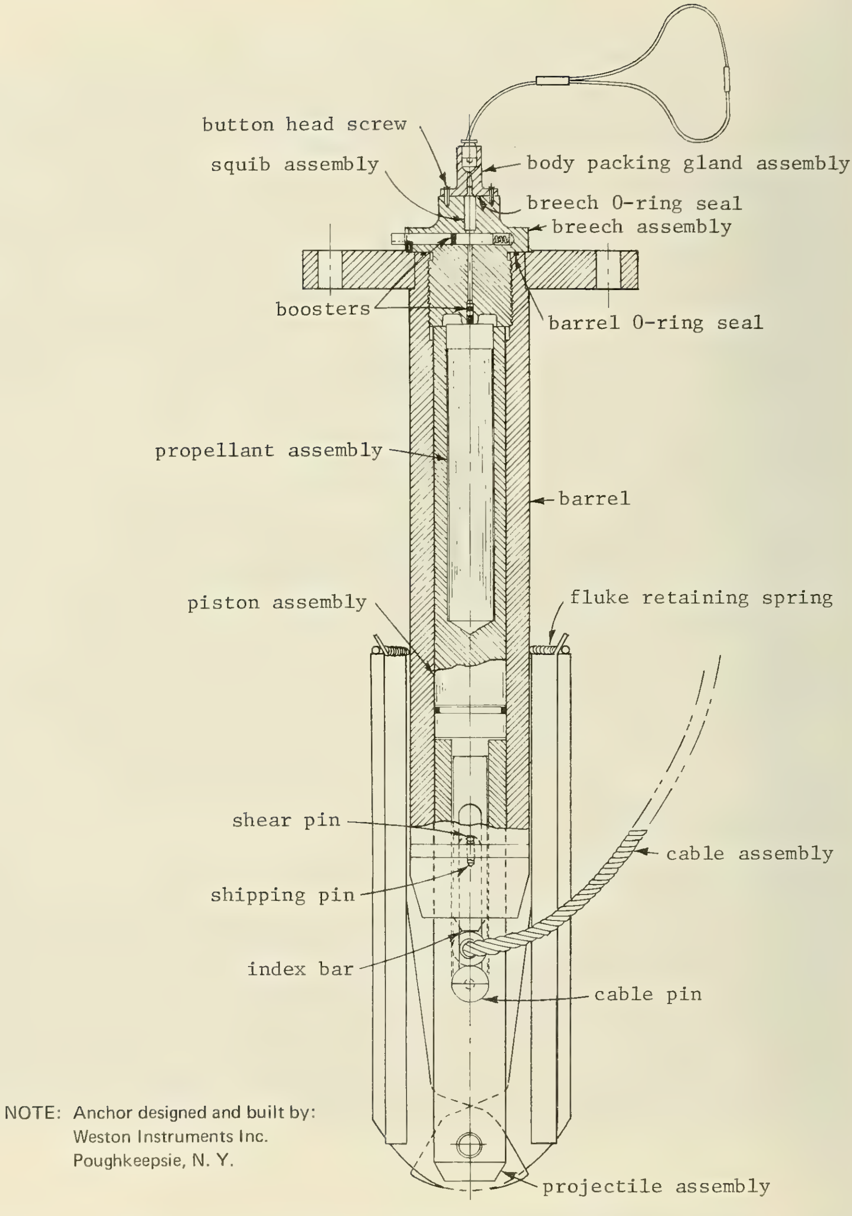

Figure 17. 20,000-pound propellant-actuated embedment anchor, (Dantz, 1968).

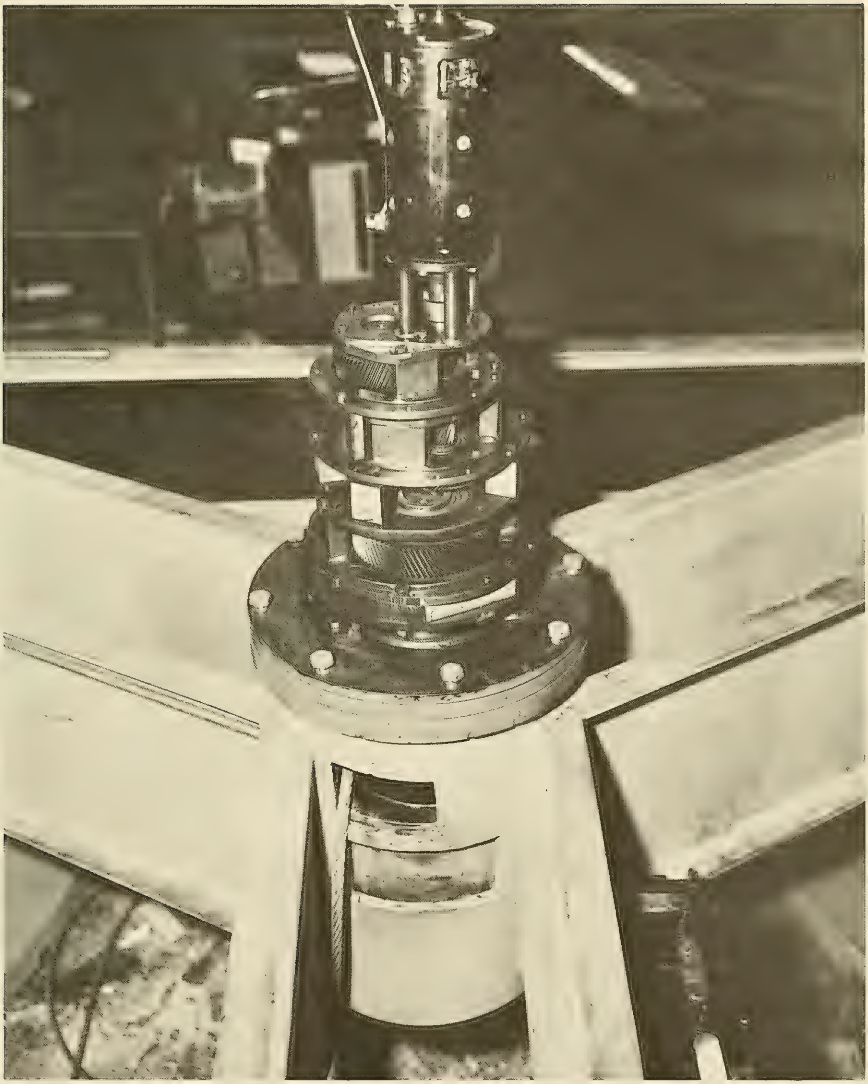

Figure 18. 24-volt DC motor and gear reduction.

In no single test did all of the components function as a complete system. However, each component performed separately as intended, at least once. Most of the problems concerned the explosive anchors. For example, the contractor-procured anchors were found to be improperly heat-treated, and they failed under high acceleration induced stress. This fault was corrected after two tests. Recoil of the anchor gun assembly was restricted by the tripod framework and caused high stresses in the anchor and the framework. Problems were encountered with the cable-payout system. The cable bale had to provide a sufficient amount of cable for the anchor, whose depth of penetration varied for each shot, and a means had to be provided for the rewind mechanism to draw off the remaining cable and develop a pretension in the line. A new frame was designed specifically to accommodate a workable cable-payout system. The redesigned structure then performed according to design.

The activator unit initially malfunctioned due to an intermittently operating transistor. After the trouble was remedied, the unit functioned according to design. The battery power source initially was used without a protective container (heavy grease provided insulation from sea water) and was subject to deterioration. Later a battery container filled with transformer oil and covered with a flexible neoprene top to make the system pressure compensated was used and prevented deterioration of the batteries. The specially designed stern roller was not used in tests with the PADLOCK. However, it was used in other deep sea operations where conditions were similar to those to be experienced with the PADLOCK in deep water. The roller was found to adequately handle synthetic rope, wire cable, chain, and shackle connectors made up as a single string. It also mentioned the line load at all times and provided an outboard means of preventing a vertical line from chafing the vessel's bumper plate.

The report, (Dantz, 1968, p. 19), concluded that:

1. "In general, the PADLOCK Anchor System has been demonstrated to be a workable concept.

2. "The power supply, rewind mechanism, and cable system are workable and fully dependable.

3. "The activator unit is operational, water tight at pressures up to 500 psi (no upper limit established), and is not affected by the shock loads imposed by the detonation of the embedment anchors.

4. "According to a limited number of tests, the reliability of all the components functioning as a complete system is very low, mainly because the reliability of the embedment anchors was unsatisfactory."

It was recommended that further effort be suspended until the reliability of propellant-actuated embedment anchors was improved.

Further developments and study in the deep ocean anchoring program at NCEL make it possible to view the contributions and prospects of the PADLOCK system with a broader perspective. The tripod framework and its rewind mechanism is a development that can be utilized to obtain increased capacity of deep ocean direct embedment anchors whether they be improved explosive anchors or some other type. It can accomplish this increase by effectively combining and mobilizing the holding action of groups of anchors in a module. Also, it can provide the bearing capability needed for some constructions. Though not in the program effort at the current time, the principle of operation and the hardware are available for reapplication when appropriate.

Other developments emanating from the PADLOCK program also are beneficial to the ongoing effort. The stern roller is proving valuable in handling loads in deep sea operations similar to those encountered in placing anchors. Features of the activator unit are adaptable to command other functioning parts of deep water anchors. The battery power unit principle is being employed in the current vibratory anchor program.

VIBRATORY ANCHOR

Background

The current deep water anchoring program is centered upon the vibratory anchor concept. Other anchor approaches are not excluded from the program but rather are in abeyance. The anchor designs discussed or elements thereof, plus still other designs may well be needed and used to achieve the range of anchoring capability essential to future ocean construction. However, weighing such factors as current knowledge and state-of-the-art skills, the vibratory anchor appears to offer the greatest early return.

The principle of driving piles by vibration into the soil on land has been employed for more than a decade. The idea of embedding anchors by this method suggested itself with the successful driving of piles and coring tools by vibration. Of particular note, as it applies to deep water applications, was the accomplishment of obtaining core samples in 3000 feet of water off the California coast with a vibracorer (Winterer, 1967).

Three major considerations are favorable to the vibratory anchor concept. First, it permits power to be applied throughout the embedment phase of placement. Thus, it should be able to better accommodate to and compensate for varying resistances as it penetrates into the seafloor than a single burst of energy embedment anchor. Second, by virtue of the delibrate steady embedment process afforded by the extended power base of operation, the fluke design developed for the free-fall anchor concept seems to be more readily adaptable to the vibratory principle. Third, instrumentation to measure the amount and the rate of penetration is more readily adaptable to the vibratory anchor than other conceived direct embedment type anchors. This information

is highly important because it provides confirmation of satisfactory implantment of the anchor plus reasonable data on which to base calculations to predict holding capacity. Still another consideration is that the cost of the vibratory anchor is low compared to explosive anchors of comparable capacity if the normally reusable gun-reaction component of the explosive anchor is considered to be expendable in deep water.

There are evident detrimental features to the vibratory anchor. The present nature of the concept dictates that it be of a long slender configuration. This factor makes it awkward to handle on shipboard and presents difficulties in stabilizing and orienting it while on the seafloor prior to embedment. The size, power, and weight limitations from a practical handling and control standpoint seem to limit the vibratory anchor's holding ability to moderate capacities. Nevertheless, a workable direct embedment anchor with the reliable and predictable capacity anticipated of the vibratory anchor would be of immense immediate value for many current ocean constructions.

The initial design and fabrication of vibratory anchor prototypes were accomplished under contract to Ocean Science and Engineering Corporation. The Contractor conducted demonstration tests. The Laboratory subsequently received the prototype hardware and initiated a program that involved testing and modifying the initial design. Also, an analytical investigation was begun to optimize the vibratory anchor system for different seafloor conditions.

Description

The first generation vibrator anchor design is a long slender metal construction comprised of four basic subsystems; a vibrator, a fluke-shaft assembly, a support guidance frame, and a storage battery power pack, Figure 19.

The vibrator consists of two eccentrics enclosed in a pressure resistant rectangular aluminum block and two motors, each of 4 hp and housed in a pressure resistant aluminum cylinder attached to the block. The eccentrics generate a peak driving force of 10,000 pounds. The vibrator and housings are bolted to the top of the fluke-shaft assembly.

The fluke-shaft assembly with the vibrator attached is about 24 feet long. The fluke is a special rotating design (developed during the free-fall anchor program) that provides minimum resistance to penetration, then keys with little vertical displacement to a position presenting a maximum resistance to breakout, Figure 20. It is made of 1/2-inch thick T-1 steel plate cut in two half-circles and one 1/4-circle that are welded together along their diameters to form a "Y"-shape with three 120^{o} angles. When in the penetrating position, the fluke is firmly fixed to the shaft by a locking/tripping mechanism. This attachment must be maintained very rigidly to ensure that the vibration is transmitted to the fluke. The shaft is a 21-foot long, 3-inch, Schedule 80 pipe with special weldments at each end for attachment of the fluke and the vibrator.

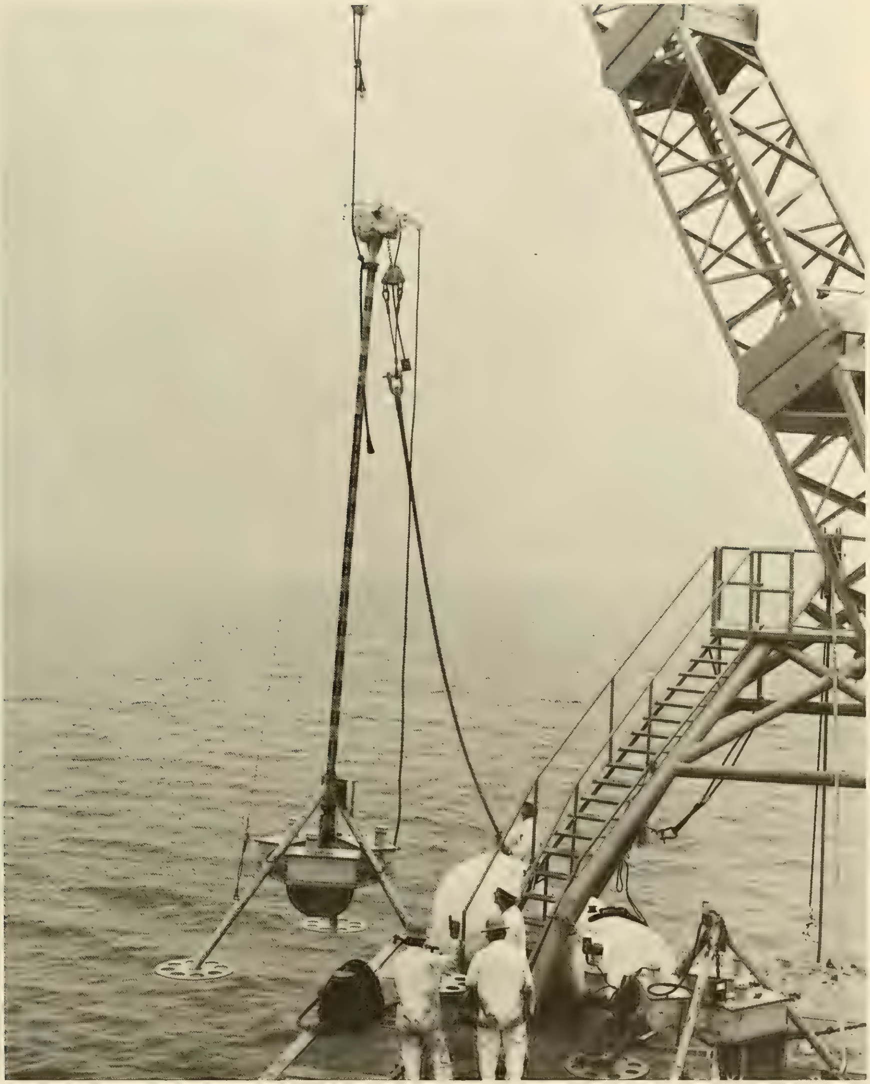

Figure 19. Prototype vibratory anchor.

Figure 20. Quick keying fluke used with the vibratory anchor.

The support guidance frame is a tubular tripod construction that contains the battery power pack and orients and guides the fluke-shaft during the embedment phase of operation. Guidance is provided by a sleeve at the peak of the tripod, 6 feet off the seafloor. The tripod has 3-foot diameter circular bearing pads welded to the end of each leg to form an equilateral triangular base. The power pack batteries are contained in three oil-filled pressure-compensated steel boxes mounted in a rack that is fixed to the tripod 3 feet off the seafloor. The battery boxes are interconnected by electrical leads to provide 240-volt, 30-ampere service to the vibrator unit via a cable.

Appurtenant Instruments

Instrumentation permitting remote sensing of the attitude of the vibratory anchor when it rests on the seafloor and its penetration is important. The anchor must remain upright prior to and during the placement process. Also, the anchor capacity is highly dependent upon the embedment achieved. The confirmation of embedment and knowledge of the amount of penetration is necessary to predict the performance of the anchor. The need for developing an attitude sensor was emphasized during tests of the vibratory anchor in deep water. On some occasions, the anchor overturned and the tests were unsuccessful.

A displacement monitoring system and an attitude sensor were developed during testing of the vibratory anchor. The displacement monitoring system, Figure 21, is comprised of a spring-loaded wire take-up mechanism, a rotating potentiometer, and a pinger. The wire is stretched between the anchor vibratory unit and the take-up mechanism which is mounted on the support guidance frame. In action, the anchor is displaced relative to the support guidance frame. The wire is pulled into the device by the spring loaded take-up mechanism and rotates the potentiometer. The potentiometer is in an electrical circuit with the pinger so the anchor's movement changes the ping rate. The ping rate is detected with a hydrophone, recorded and later translated into terms defining the linear displacement of the anchor fluke.

The first displacement monitoring system was accurate to within 6 inches of displacement, which is sufficient to confirm embedment. However, data for analytical studies used in efforts to optimize the fluke size-depth relationship require more precise breakout displacement measurements. Also, because loads applied during field testing are of a transient nature, it was desirable to measure to within at least 1 inch the amount of displacements caused by transient loads. The necessary increase in displacement sensitivity was accomplished by changing the resistive range of the potentiometer. With this change, the device measures displacements accurately to within about 2 inches when the fluke is near the water seafloor interface and about 1/2 inch when the fluke is fully embedded. The variation in accuracy is due to the difference in the ping frequency that transmits the displacement information. The instrumentation is designed in such a manner the ping rate is faster and thus more accurate when the fluke is in the more critical zone of embedment.

Figure 21. Displacement monitoring system.

Initial efforts toward providing an attitude sensor focused on a standard pendulum-type device. The vibration of the anchor, however, prevented this device from being successfully employed. A simple solution to the problem was achieved by incorporating a mercury switch into the displacement monitoring system's electrical circuit. This switch is set so that when the tilt of the anchor exceeds a specified angle, the pinger of the displacement monitor is turned off. This essentially signals the shipboard monitor that the anchor is resting at a precarious angle or that it has overturned.

General Test Program and Procedures

The investigation of the vibratory anchor design first involved contractor testing to confirm the overall functionality and integrity of the design for operation in shallow and deep water. Contractor testing included shallow and deep water tests in sand and clay seafloors. Upon receiving hardware deliverable under terms of the contract, NCEL continued the test program in a variety of seafloor and water depth conditions. A summary of all testing conducted to date is presented in Table 2.

The purpose of the Laboratory testing is to determine the capabilities and limitations of the initial vibratory anchor design and to establish criteria for improvements. The functioning and performance of the anchor system components were examined individually and collectively. Also, operational aspects of handling and lowering the anchor from various work platforms at sea were noted.

The test program for the full-scale vibratory anchor prototypes has been somewhat dictated by the availability of work platforms and other support activities. As a consequence, the anchor has been tested with a variety of equipment and under a wide range of conditions.

Though details of procedures differed to adjust to particular test objectives and the support equipment used, the general procedure for tests were similar. For the shallow water tests (less than 100 feet) the work platform, ship or barge, was held firmly in place either at dockside or in a two-point moor at sea. Then the anchor was assembled and readied on deck, lifted over the side by a crane or ship boom and lowered to the seafloor by a winch. Once on the seafloor the anchor was activated by power supplied on the deck or by the battery power pack contained by the support guidance frame. If embedment was successful, uplift loads were applied through a multiple part line and sheave rigging arrangement. A dynamometer was placed in the system to measure the applied loads. An example of such rigging is shown in Figure 22.

Loads were applied continuously until breakout. In some tests, attempts were made to hold the applied loads steady for a period of time before applying the next higher load increment. However, movement of the work platform due to ocean swells made it impossible to hold loads perfectly steady even though in some tests a length of synthetic rope was used as part of the load line to attenuate the effect of ship heaving on the anchor.

Table 2. Summary of vibratory anchor penetration and breakout tests.

Operation	Water Depth (feet)	Soil Type	Penetration (ft)	Maximum Measured Load (kips)	Comments
I July 1968	33	Harbor soil	16	NA	Flukes welded closed 9 minutes of vibration
	33	Harbor soil	12	62	25 minutes of vibration
II Aug 1968	unknown	Sand	16	NA	16 feet of penetration in 2 minutes
III Nov 1968	2460	unknown	unknown	52*	Anchor assembly functioned satisfactorily
IV March 1969	1000	unknown	none	--	Motor did not activate
	1000	unknown	none	--	Motors activated but ship motion dragged anchor preventing embedment
V May 1969	40	Sand	none	--	Operations were conducted with support of Naval Underwater Center. Attempt to embed anchor was unsuccessful due to fluke linkage problem and electric cable failure.

continued

* Fluke did not open.

Table 2. Summary of vibratory anchor penetration and breakout tests (continued).

Operation	Water Depth (feet)	Soil Type	Penetration (ft)	Maximum Measured Load (kips)	Comments
VI May 1969	500	Clay	15	5	All anchor components functioned satisfactorily. Soil extremely weak.
VII Aug-Sep 1969	55	Sandy Silt	4½	14	Faulty load measurement
	43	Sandy Silt	4½	40	Linkage between fluke and shaft broke
	43	Sandy Silt	2	18	Linkage between fluke and shaft broke
	43	Sandy Silt	7	62	Linkage failed--fluke lost
	52	Sandy Silt	6	70	Relatively high holding capacity with small penetration
	52	Sandy Silt	5	57	Relatively high holding capacity with small penetration
VIII March 1970	95	Clay-silt	9½	60	Penetration limited by stiff sediment
	95	Clay-silt	5½	9	Vibrator failed, fluke did not open
	95	Clay-silt	9½	50	Penetration limited by stiff sediment
	95	Clay-silt	4	12	Vibrator failed

Figure 22. Rigging for load application.

Procedures for the limited number of deep water tests were similar but the work platform was not anchored. Instead, marker buoys were dropped prior to the test. When the anchor assembly reached the seafloor the ship attempted to maintain position with respect to the buoys to keep from dragging the anchor or tipping it prior to embedment. Power for the deep water tests was supplied by the battery power pack contained with the support guidance frame. One other important step was followed in the deep water tests. The proximity of the vibratory anchor to the bottom was monitored by the ship's precision depth recorder unit as the anchor was being lowered. Once the anchor was on the seafloor, the functioning of the vibrator was monitored with the same equipment.

Test Results

The most noteworthy events of the test program to date are reviewed as follows:

Operation I - Long Beach Harbor, harbor soil. Two tests were conducted by OSE to demonstrate the vibratory anchor's operating capability as required by the contract. The operation was conducted in Long Beach Harbor at a water depth of 33 feet.

For the first test, the fluke was welded to maintain the penetrating position during breakout. Sixteen feet of embedment was achieved with nine minutes of vibrator operation. A peak line tension of 15,000 pounds was measured during breakout of the anchor with the fluke fixed in the penetrating position. The second test was performed with the fluke rigged for normal operation. Twelve feet of penetration was achieved with 25 minutes of vibrator operation. A line tension of 36,000 pounds was applied to the anchor and maintained for one hour and forty-five minutes. Later, a peak line tension of 62,000 pounds was applied to the anchor. The anchor was eventually recovered by water jetting around the anchor so that the winch could pull the anchor free.

Operation II - Santa Catalina Island, sand. One penetration test was conducted by OSE to demonstrate the anchor's ability to perform satisfactorily in sandy seafloors. The operation was conducted at Emerald Bay at Santa Catalina Island in shallow water from a small chartered power boat that did not have the capability to apply large test loads.

Several drop tests were performed prior to the penetration test to check the anchor's stability when striking the seafloor, and to test the motor starting mechanism and the drop release mechanism. These features checked out satisfactorily. After completing this phase, the anchor was readied for the penetration test. Sixteen feet of embedment was achieved in two minutes of vibrator operation. No holding capacity test was performed; divers freed the anchor from the bottom with a high pressure water jet.

Operation III - Santa Catalina Channel, deep water. The objective of this test was to demonstrate both the anchor's overall functionality during deployment from a ship at sea and its ability to operate at deep sea water depths. The operation was conducted aboard OSE's vessel, the Oceaneer in the Catalina Channel in a water depth of 2460 feet. Meteorological data at initiation of the test were a Sea State 4 and an 18-knot wind. Conditions decreased during the test period to a Sea State 1 and a 7-knot wind.

A marker buoy was placed as a reference to help the Oceaneer maintain station during the operation. The anchor assembly was lowered to the seafloor taking 25 minutes. The vibrator successfully activated and ran for over one hour before the batteries ran down. Deck gear was rigged to measure anchor line tensions and load was applied by moving the ship ahead. A peak line tension of 52,300 pounds was measured during anchor breakout. After breakout, the anchor assembly was returned to the deck and it was determined that the fluke had not tripped.

Two observations are pertinent with respect to this test. First, the measured load is highly suspect due to manner in which it was determined. A 0-20,000 pound capacity hydrostatic load cell was rigged so as to measure the force necessary to deflect the main anchor line between two reference positions 24 feet apart. An 1800-pound force deflected the anchor line 3 inches and by trigonometric relationship was translated by the contractor into the 52,300-pound measured force. Second, the anchor line was found to be wrapped around the vibrator when it was returned to the deck. The entanglement is believed to have prevented the fluke tripping mechanism from being activated.

Operation IV - Santa Barbara Channel, deep water. The primary goal of this operation was to establish the vibratory anchor as the anchor of a taut-line guide system for lowering objects to the seafloor. The operation was conducted in the Santa Barbara Channel at an approximate water depth of 1000 feet. The USS Cocopa (ATF 101) served as the work platform.

The anchor was lowered to the seafloor twice with the ship in a free drift. The anchor was not successfully embedded on either attempt. The first time, the motors did not activate probably because the anchor toppled. On the second attempt, the motors activated but the motion of the ship caused the anchor to be dragged along the seafloor. Thus, it is believed that the dragging motion was responsible for lack of success in both attempts.

Operation V - San Clemente Island, sand. The goal of this operation was to evaluate the anchor under long term constant loading conditions similar to those that would be experienced in service. Operations were performed in Wilson's Cove at San Clemente Island in 30-50 feet of water aboard a Naval Underwater Center (NUC) barge.

An attempt to embed the anchor in a sand bottom was unsuccessful. Two causes were identified. The linkage between the fluke and shaft was not tight, therefore, the shaft and fluke were not vibrating as a unit resulting in a drastic reduction of driving energy being transmitted to the soil. Rather, the energy was being used to drive the fluke in a hammer action, which in sands is not as efficient as vibration for achieving penetration. In addition, the electrical cable transmitting power became overloaded and failed.

Operation VI - Seneca Lake, clay. The primary objective was to determine the functionality and holding capacity of the vibratory anchor for its possible application in a long-term mooring for the Naval Underwater Sound Laboratory (NUSL). Operations were conducted aboard an NUSL barge on Seneca Lake, New York at a location where the water was 500 feet deep. The bottom consisted of a very weak clayey bottom ooze.

The anchor was lowered to the bottom with a crane aboard the barge under carefully controlled conditions. The barge was firmly anchored in a four-point moor. Power to the vibrator was supplied by a generator on the barge through an electrical cable.

The anchor easily penetrated the weak sediments to the limit permitted by the support guidance frame, in this instance 15 feet. Penetration was determined with the newly developed displacement monitoring system. Loading was applied and breakout occurred at a peak load of 5000 pounds. On retrieval, it was established that the fluke tripping mechanism had functioned satisfactorily and the fluke had "keyed" to the maximum resistance to pull out position.

The Seneca Lake operation demonstrated that the anchor was functional for use in the lake even though the holding capacity was less than desired. Also, it confirmed the functionality of the anchor in soft sediments. Seneca Lake presented a unique problem, not likely to be duplicated in the deep sea. However, the data obtained was valuable because it indicated that the present anchor is not able to provide acceptable holding capacities in weak sediments. The weak sediment problem was studied theoretically, and the results of the study are being incorporated in the future program.

Operation VII - Port Hueneme, sandy-silt. The objective of this operation was to conduct holding capacity breakout tests in a cohesionless seafloor under the best control conditions possible with available equipment. Operations were conducted aboard the NCEL warping tug in water depths within the 40 to 60 foot range. The location was the NCEL shallow water test site near Port Hueneme in the Santa Barbara Channel.

For each test, the warping tug was in a tight 2-point moor. The anchor assembly was lowered to the seafloor and the vibrator was activated by a generator onboard the tug to eliminate battery recharging. After the anchor was embedded, divers removed the vibrator and bolted on a lifting padeye through which test loads could be applied directly to the anchor shaft. A 20-foot nylon line was placed in the anchor cable to attenuate the dynamic effects caused by wave action. Then, loads were applied using the three-drum winch on the tug and measured with a strain gaged load cell. Line tensions were recorded continuously with a pen-type strip chart recorder. Displacements during breakout were not measured; however, diver observation was used to determine maximum anchor embedment for each test prior to breakout.

Five successful embedments were achieved that resulted in four successful breakout tests. A mechanical linkage failure during one test prevented the embedded fluke from being extracted. Embedment depths ranged from 2 to 7 feet measured from the seafloor to the centerline of the fluke. Breakout forces ranged from 18 kips for the fluke embedded 1½ feet to 70 kips for a fluke embedded 5½ feet. The fluke that was embedded the deepest (6½ feet after keying) is the one that broke off and was lost. It resisted forces to 62 kips before the linkage connector failed at the fluke.

Operation VIII - Pitas Point, clay-silt. The objective of this operation was to conduct holding capacity breakout tests in a seafloor sediment that exhibits plastic behavior under the best control conditions possible with available equipment. Operations were conducted aboard the USS Molala (ATF 106) in 95 feet of water. The location was the Pitas Point test site in the Santa Barbara Channel near Ventura. Seas were calm throughout the operation period.

The Molala was anchored in a tight 2-point moor during all testing. For each test the vibrator was activated and powered through an electrical cable leading to a DC generator on the ship. The surface power was used to eliminate the necessity of recharging the batteries for each test. The vibrator was allowed to run until the maximum embedment was achieved as limited by sediment strength or vibrator failures. Penetration during the vibration phase was measured using the displacement monitoring system. Direct uplift loads were applied with the ship's capstan pulling through the salvage beach gear (an 8-to-1 block and tackle arrangement). Both the upward displacement of the anchor fluke and line tensions were measured and recorded continuously.

Four tests of the vibratory anchor were conducted. In the first test the anchor embedded 9 feet 6 inches. A short term to breakout test load was applied. Six inches of penetration was lost in "keying" the fluke. The peak anchor line tension measured was 58,000 pounds. One higher tension occurred but the amount was not recorded because it exceeded the scale of the recorder unit before adjustments could be made. However, at the time of occurrence, the anchor fluke was displaced 20 inches and subsequently worked out of the bottom under lower loads. Typical loads and accompanying displacements are shown in Figure 23.

In the second test, thirty-five minutes of vibration produced only 5 feet 6 inches of penetration. Then, a sharp increase in the current to the vibrator indicated that a short had occurred in the electrical circuit. A 9,000 pound cable tension pulled the anchor free. When the anchor was recovered, it was learned that the fluke had not keyed. A shear pin in the tripping mechanism had wedged in the shaft and blocked the tripping slug.

A refurbished vibrator was used for the third test. Embedment of 9 feet 6 inches was attained. After "keying" the fluke depth was 8 feet 4 inches. In this test, attempts were made to hold peak cable tensions between 20 and 30 kips so that longer term holding performance would be measured. Efforts were partially successful. The anchor extracted after the breakout test was prolonged over a two-hour time frame. Peaks exceeded 30,000 pounds several times and each peak of this magnitude caused a few inches of displacement. One peak that reached 47,000 pounds resulted in a sudden 20-inch displacement. About 50 load peaks between 20,000 to 50,000 pounds were experienced by the anchor. The mean of the peaks was approximately 25,000 pounds.

In the fourth test, as during the second test, the vibratory unit failed. An embedment of 4 feet was attained. As load was applied, the fluke keyed satisfactorily. Extraction occurred as a peak load of about 12,000 pounds was reached.

A significant aspect of the Operation VIII tests is that good vibrator performance was obtained the first time the vibratory units were used (tests one and three). When the units were used a second time, (tests two and four) they failed. After the operation, the units were dissassembled and water was found to have penetrated into the eccentric's chamber.

Optimization of Design

Background. The need to reliably predict anchor penetration and resistance in a variety of seafloors is paramount if an optimized vibratory anchor system is to be achieved. The basic changes in the first generation vibratory anchor design to achieve optimization are dependent upon the results of an analytical study using basic foundation engineering principles and engineering judgment.

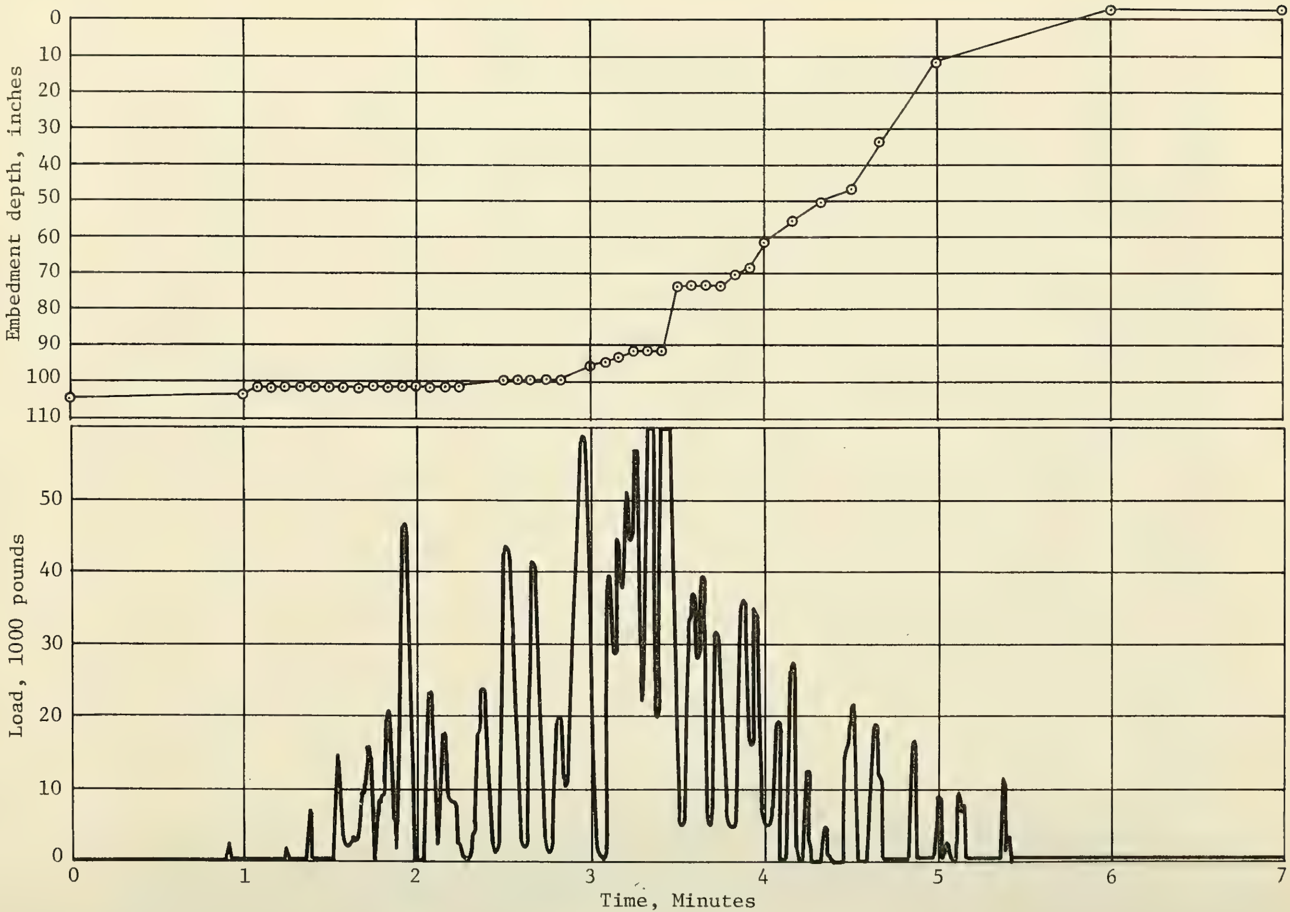

Figure 23. Typical load and displacement data.

Information on the breakout forces necessary to extract objects that are embedded in the seafloor is not plentiful; however, there is considerable information on this subject regarding terrestrial soils. Unfortunately, most of this information is related to the breakout resistance of shallowly embedded objects. Common practice has been to extend shallow breakout theory to the case of deeply embedded objects. This procedure is not applicable to extending shallow foundation design theory to deep foundation theory so it is probable that this procedure is not applicable to the similar problem of anchor breakout. Therefore, new analytical techniques were required to determine the breakout resistance of deeply embedded objects.

Results of the research on shallow anchors indicate that such anchors form failure surfaces that are dependent upon soil type and soil density. Small-scale model tests at Duke University (Equivel-Diaz, 1967; Ali, 1968; and Bhatnagar, 1969) show that the shape shown in Figure 24 occurs only in the case of relatively shallow anchors in dense sand or stiff clay. For shallow anchors in loose sand or soft clay, the slip surface, though not clearly established, is closer to being a vertical cylinder around the perimeter of the anchor.

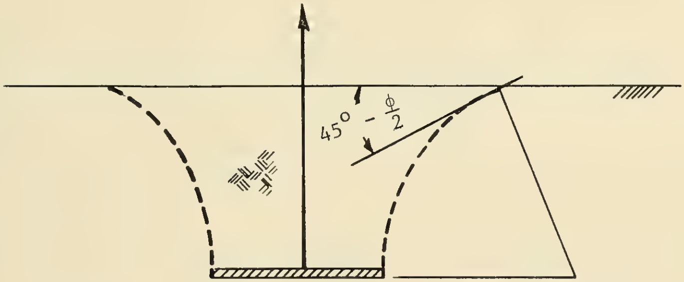

Figure 24. Slip surface for a shallowly embedded circular plate.

Deeply embedded anchors do not fail the soil in general shear failure such as that shown in Figure 24, regardless of the relative density of the soil. Experiments indicate that they can be moved vertically for considerable distances by producing a failure pattern, Figure 25, similar to punching shear failures in deep foundations (Vesic, (1969). Only after being pulled up to relatively shallow depths may they eventually produce general shear failures such as shown in Figure 24.

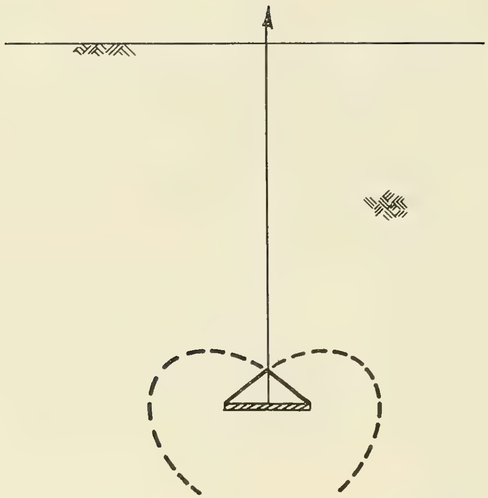

Figure 25. Slip surface for a deeply embedded circular plate.

As presented in the section on Tests and Results, NCEL and OS&E have tested the anchor in several types of soils. In some instances very good penetration did not produce adequate holding capacities. In other instances, rather poor penetration produced relatively high holding capacities. One extreme example is a series of tests conducted at Seneca Lake by OS&E where penetrations were not limited. (This particular test series was not part of the Laboratory program and is not included in the test results.) An anchor system similar to the NCEL vibratory anchor achieved exceptional penetrations (over 50 feet), but breakout resistances were minimal (less than 15,000 pounds). It should be noted that in these tests a more powerful vibrator unit was used and the support guidance frame was not used thus permitting the vibrator unit to follow the fluke-shaft assembly into the soft sediments. At the other extreme are tests conducted by NCEL in a sandy silt where desired penetrations were not achieved, but results indicated that the

holding capacities would have been more than adequate if the desired penetrations had been achieved. From these tests it was evident that the first generation vibratory anchor is not a balanced design; i.e., one that matches the energy required to achieve proper embedment with fluke size to obtain the rated holding capacity in different types of seafloors.

A vibratory anchor with a balanced design would, for a fixed amount of energy, embed into most seafloors and develop the same rated holding capacity. Unfortunately, in some seafloors, such as coral or rock, the anchor may not be functional because all available energy might be expended with little or no penetration and no consequent holding capacity. However an approach to an optimum vibratory anchor should be possible for most seafloor sediment conditions. To develop such a design, the relationships between fluke size, depth of embedment, breakout force, vibrator driving capability, and soil characteristics must be established for the soil types to be encountered. Once these relationships are established, a vibrator can be selected that has sufficient energy or force to drive different sized flukes to appropriate soil depths to achieve the desired capacity. The resulting vibratory anchor design will utilize a vibrator of one size with a fixed amount of energy available and have different fluke sizes for different seafloor soils (i.e., large flukes for low strength soils and small flukes for high strength soils). This accommodation will best utilize the fixed amount of energy available.

Analytical Procedure. The sequence of events for the attainment of an optimum vibratory anchorage system was:

(1) Determine the relationship between breakout force, fluke size, depth of embedment, and soil shear strength for cohesive and non-cohesive sediments.

(2) Determine the penetration capabilities of the existing vibrator (10 kip force) for various fluke sizes and sediment types.

(3) Determine the adequacy of the existing vibrator to achieve desired penetration and capacity.

(4) Determine the most suitable fluke sizes to utilize the fixed amount of force available (10 kip) for both cohesive and cohesionless soils.

The first step of the optimization was the analysis of the breakout resistance of embedded anchors. An analytical procedure, based on Vesic's (1969) analysis of the problem of the expansion of a spherical cavity close to the surface of a semi-infinite plastic solid, was used to determine the relationships between breakout force, fluke size, depth

of embedment and soil characteristics. Vesic's theoretical analysis was chosen because his results show good agreement with model tests of anchor breakout in the case of soft clays and loose sands (both typifying ocean sediments).

Vesic's analysis was based upon the assumption that the shape of the slip surface during pullout is as shown in Figure 24. This type of failure is referred to as general shear and as previously mentioned in the Background section, occurs with "shallow" anchors. Vesic's theoretical solution gives the ultimate radial pressure needed to breakout a spherical cavity below the surface of a solid. The relationship is as follows:

$$q_o = c\bar{N}_c + \gamma_b D\bar{N}_q \qquad (1)$$

where q_o = radial pressure (holding capacity)

c = soil cohesion

$\bar{N}_c = F_c$

$\bar{N}_q = F_q + 1/2\ D/B$

F_c, F_q = cavity breakout factors

γ_b = buoyant unit weight of the soil

D = embedment depth

B = circular plate diameter

For each soil, there is a characteristic relative depth D/B (D/B = ratio of depth of embedment to fluke diameter) beyond which anchor plates start behaving as "deep" anchors and beyond which breakout factors reach constant final values (Vesic, 1969). The failure pattern for deep anchors is similar to that occurring under deep foundations and is referred to as a punching type failure, Figure 25. To account for the changes in failure patterns, Vesic's results were tempered with engineering judgment and used in this analysis. The analysis is best explained by referring to Figures 26 and 27 where graphs of long term static breakout force versus depth of embedment for various fluke sizes are presented for an ideal sand and an ideal clay.

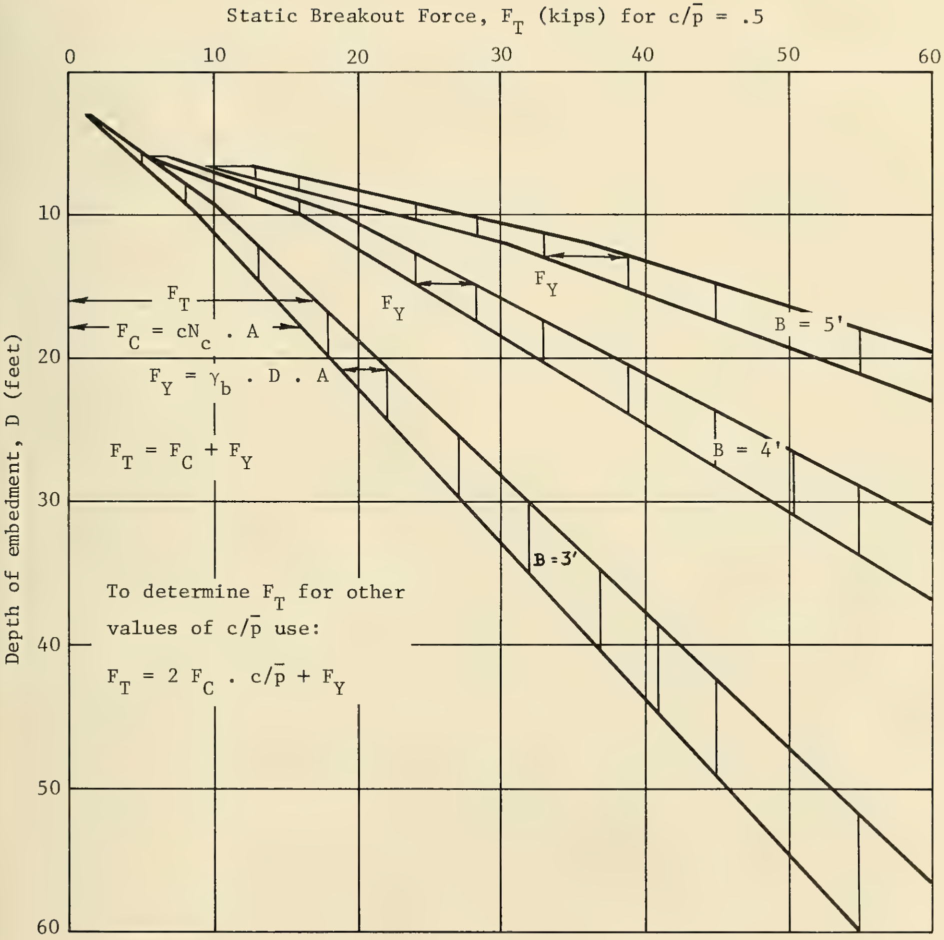

Figure 26. Breakout force versus depth of embedment for an ideal clay; ϕ = o, γ_T = 90 pcf.

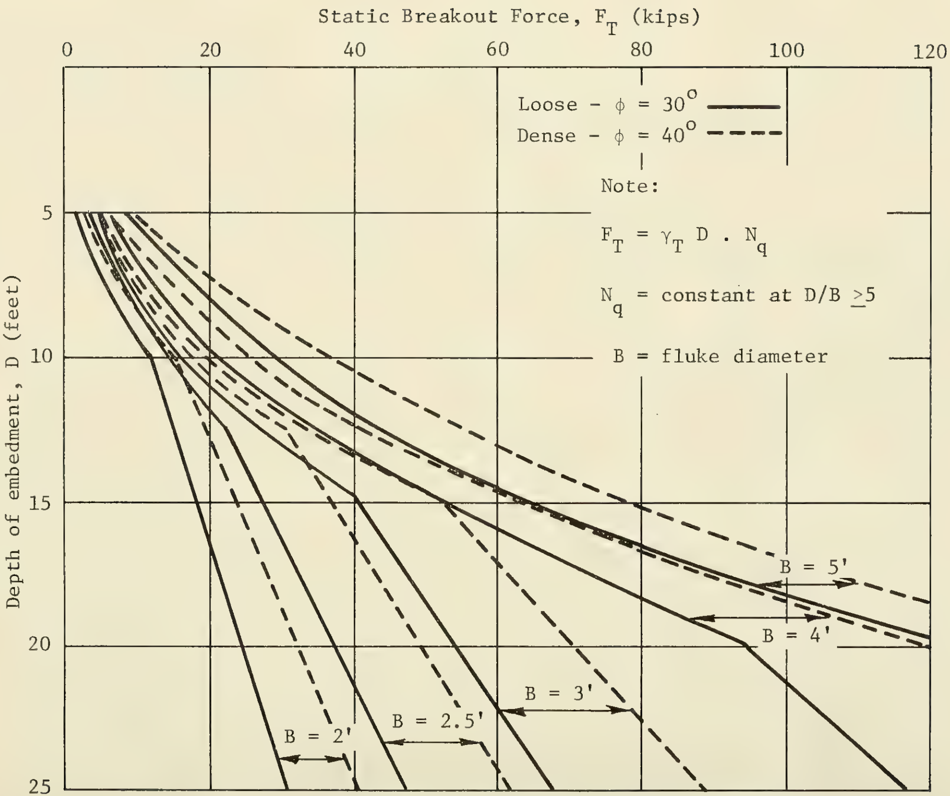

Figure 27. Breakout force versus depth of embedment for an ideal sand, c = o, γ_T = 110 pcf.

To simplify the analysis for ideal clay, Figure 26, depth was plotted for a single $c/\bar{p}$ ratio of 0.5 ($c/\bar{p}$ = ratio of undrained shear strength to vertical effective pressure). Most seafloor clays are normally consolidated and can be classified by a constant $c/\bar{p}$ ratio, whereas most terrestrial clays are overconsolidated and exhibit variable $c/\bar{p}$ ratios with depth. The results were plotted to separate the cohesive (F_C) and the overburden (F_Y) components of the total breakout force (F_T) and to permit calculation of breakout force for clays with various $c/\bar{p}$ ratios. Breakout force was calculated using the breakout factors provided by Vesic, in Equation 1; however, the breakout factor $\bar{N}_c$ was limited to a maximum value of 12. Previous researchers (McKenzie, 1955; Hansen, 1953) have shown that "deep" anchor blocks exhibit breakout factors N_c of 11 to 12 which roughly correspond to bearing capacity factors for "deep" foudations (Skempton, 1959). The points at which anchor behavior changes from a shallow to a deep anchor are indicated by slope changes in the lines of equal fluke size.

Figure 27 presents plots of breakout force versus depth for an ideal sand initially in the loose and dense state corresponding to friction angles of 30 and 40^o, respectively. Most seafloor sands are thought to fall within this range.

As previously mentioned, available data suggest that the limiting relative depth, D/B, in sand, where punching failure begins, may increase from 2 in loose sand to over 10 in dense sand. Seafloor sands will generally be of low density; however, anchor embedment by vibration will cause densification. Being moderately conservative, all sands prior to anchor breakout are assumed to be of medium density. It has been shown (Baker and Kondner, 1966; Kalajian, 1969) that sands of medium density will change from a shallow to a deep anchor at a relative depth D/B of approximately 5. Therefore, for relative depths $\geq D/B = 5$, the breakout factors N_q used in Equation 1 are constant.

The points at which anchor behavior changes from a shallow to a deep anchor (where N_q = const.) are noted by slope changes in the lines of equal fluke size.

The breakout forces presented are long-term static forces and do not take into account the effects of creep in clays and loading conditions other than static. Modifications of the breakout forces in consideration of these factors will involve considerable engineering judgment and a thorough understanding of the loads applied to the anchor mooring system.

The second step was to analyze the penetration of vibratory anchors. A simplified method for predicting the depth of embedment is to equate vibrator driving force to static soil resistance. This technique is based on experience gained with vibratory pile drivers, which under tough driving conditions, fail to advance the pile further into the soil when the total weight plus the maximum driving force generated by the vibrator is less than the total static soil resistance to penetration (Schmid, 1969).

The equation used to calculate anchor penetration in clay is:

$$Q_{ult} = A_s \cdot c_{rem} + A_F \cdot c \tag{2}$$

where Q_{ult} = vibrator force (10 kip)

A_s = total surface area of anchor shaft

A_F = total surface area of fluke

c_{rem} = remolded shear strength

c = undrained shear strength

The penetration resistance of the shaft is calculated using the remolded shear strength because the fluke has passed through the region the shaft is in disturbing the soil. The fluke resistance, however, is calculated using the undrained shear strength because the fluke is penetrating into undisturbed soil. End bearing resistance was neglected because it is neglibible compared to resistance of the shaft and fluke. Equation 2 takes two forms, depending on whether the anchor is fully or partially embedded. For an embedment depth, D, greater than the total shaft length (D> 20 feet) the equation is:

$$Q_{ult} = A_s \cdot \bar{p} \cdot (c_{rem}/\bar{p}) + A_F \cdot \bar{p}\ (c/\bar{p}) \tag{3}$$

Simplifying and assuming a soil sensitivity of 2 ($c/c_{rem} = 2$) the equation is:

$$Q_{ult} = \left[A_s\ (D - 10)\ \frac{\gamma_b}{2} + (A_F \cdot D \cdot \gamma_b)\right] (c/\bar{p}) \tag{4}$$

For D <20 feet the governing equation is:

$$Q_{ult} = A_s' \cdot D \cdot \bar{p} \left(\frac{c_{rem}}{\bar{p}}\right) + A_F \cdot \bar{p}\ (c/\bar{p}) \tag{5}$$

Simplifying, the equation is

$$Q_{ult} = (A_s' \cdot \frac{D^2}{4} + A_F \cdot D)\ \gamma_b \cdot (c/\bar{p}) \tag{6}$$

where A_s' = shaft area per foot of length

$c/\bar{p}$ = ratio of undrained shear strength to effective vertical pressure

The equation used to calculate anchor penetration in sand is:

$$Q_{ult} = (A_s \cdot \bar{\sigma}_{v1} + A_F \cdot \bar{\sigma}_{v2})\ k \tan \phi \tag{7}$$

where $\bar{\sigma}_v$ = vertical effective stress

k = coefficient of passive earth pressure

ϕ = friction angle between steel and sand

Equation 7 takes two forms, one for D >20 feet, and one for D <20 feet. The equation for D >20 feet is as follows:

$$Q_{ult} = (A_s(D-10) + A_F \cdot D\ .)\ \gamma_b \cdot k \tan \phi \tag{8}$$

For D <20 feet the equation is:

$$Q_{ult} = (A'_s \cdot \frac{D^2}{2} + A_F \cdot D)\ \gamma_b \cdot k \tan \phi \tag{9}$$

The value of ϕ to be used in the above equations is independent of soil density (Lambe and Whitman, 1969, p. 143) and is taken as $\phi = 26^o$. The coefficient k is much more difficult to predict; various researchers studying the horizontal stress acting on piles in sand (Ibid, p. 501) have reported values of k from 0.5 to 3.0. It is doubtful that the full passive resistance of the soil will be developed during penetration because the fluke and shaft are small and will not cause excessive soil movement. Also, it would seem logical that the values of k used for the loose and dense sand should not differ by very much because densification of the loose sand should occur while the anchor is being embedded by vibration. Values of k between 1 and 2 are recommended (Ibid, p. 500) to calculate horizontal stress acting on piles in sand. For calculation purposes, k will be assumed to vary from 1.0 for loose sand ($\phi = 30^o$) to 1.5 for dense sand ($\phi = 40^o$).

Results of the penetration analysis are presented in Table 3 for both sand and clay. Since densities were assumed and since slight density variations have a minimal effect on penetration, only one density was used for the clay.

Determining the adequacy of the existing vibrator was the third step. Knowing the penetration capabilities of the vibratory anchor system permits the use of graphs of breakout force versus embedment depth to determine the theoretical breakout force of the vibratory anchor. The vibratory anchor penetrations presented in Table 3 refer to the embedment depths of the fluke centers prior to anchor keying. Field test results have shown that keying occurs in a distance of approximately one-half the fluke diameter (B/2). Therefore, breakout forces in Table 3 were determined from Figures 26 and 27 by using a depth of embedment equal to D_{max} - B/2.

Table 3. Summary of vibratory anchor penetration and breakout force for various fluke sizes for sand and clay.

Soil Type	Fluke Size B (ft)	Friction Angle ϕ (deg)	Shear Strength/ Normal Effective Stress $c/\bar{p}$	Penetration Before Keying D_{max} (ft)	Breakout Force F_T (kips)
Sand	2.0	30		28	34
γ_T = 110 PCF		40		21	32
c = o	2.5	30		25	45
		40		19	44
	3.0	30		20	50
		40		15	40
	4.0	30		15	38
		40		11	21
	5.0	30		11	22
		40		8	12
Clay	3.0		0.5	38	39
γ_T = 90 PCF	4.0		0.5	26	45
ϕ = o	5.0		0.5	18	47

As stated in the introduction, one of the primary goals in the development of the vibratory anchor was to achieve a holding capacity between 25 to 50 kips. Results in Table 3 indicate that this goal can be achieved by using the existing 10 kip vibrator with various size flukes for sand and clay.

The decision as to which size fluke is most suitable for various seafloor conditions depends upon two factors. First the anchor breakout resistance must be from 25 to 50 kips and second the penetration must be sufficient to minimize both the effects of scour around a long term mooring and the effects of minor upward anchor displacements due to unanticipated momentary loads.

From Table 3, it appears that a 2.5-foot fluke size satisfies the above requirements and is more desirable in sand than the comparable capacity, but shallower embedment of the 3-foot fluke. For clays, the deeper penetration of the 4-foot fluke and its comparable breakout resistance to the heavier 5-foot fluke indicates that a 4-foot fluke is the most suitable.

The fluke sizes chosen for sand and clay are based upon analytical procedures not yet verified by full scale field tests. When data from full scale tests becomes available these procedures will be updated, if necessary to improve prediction capabilities.

SUMMARY AND CONCLUSIONS

Five anchor design concepts have been explored in conjunction with the program to develop an improved deep sea mooring capability.

The knowledge gained from study of these concepts and the present status of the program are summarized as follows:

1. The "Free-fall" anchor failed to achieve sufficient holding capacity to make embedment of an anchor by free-fall impetus alone feasible. However, two things of significance to deep sea anchoring capability were gained from the work on this anchor. First, an important new fluke design that is especially suited to a direct embedment anchor was achieved. It is being used in the development of the vibratory anchor concept. Second, the free-fall cable bale payout system proved feasible and is judged to be worthy of further investigation for future placement of deep sea anchors. Elements of the "free-fall" anchor concept as they pertain to handling, placing, and utilizing deep sea anchors will continue to be considered in the program.

2. The "Pulse-jet" anchor concept was judged to be unworthy of further development. Difficulties with high-pressure, high-temperature seals plus complex critical relationships between the internal working parts of the anchor and the surrounding soil medium were judged too costly to solve. No further development is planned.

3. The small "Explosive" anchor concept was tested in shallow and deep water and was judged to be feasible for deep sea anchoring application. However, work on this small concept was suspended in favor of the vibratory anchor. The vibratory anchor offers more economical expendable parts and extended power application during embedment making it more accommodating to instrumentation for measuring penetration of the seafloor and predicting holding capacity. Future work on explosive anchors for deep sea applications appears justified to obtain greater holding capacities than practicable with the vibratory concept and/or to function in seafloors not suitable for the use of vibratory anchors.

4. The "Padlock" anchor work resulted in a tripod framework and rewind mechanism that can be used to obtain increased capacity of explosive or other direct embedment deep sea anchors once they are perfected to a satisfactory reliable level. Also, it can provide bearing capability for bottom rest structures in the sea. Ultimately, refinement and application of the "Padlock" anchor concept to meet the anchor performance requirements of high capacity complex deep sea installations is contemplated.

5. The "Vibratory" anchor currently is the center of the deep ocean anchoring development effort. A first generation design has been achieved that demonstrates the concept is feasible. The design is adaptable to instrumentation to measure and confirm its penetration into the seafloor. The new quick-keying fluke design adapted from the free-fall anchor has proved to be functional and is a major improvement over other known flukes for direct embedment anchors. Instrumentation has been developed to signal confirmation of the vibratory anchor's proper attitude prior to embedding and to signal the amount of its penetration. Analytical procedures have been devised to optimize the vibratory anchor design relating fluke size, seafloor conditions, and power requirements to achieve proper embedments.

Despite these developments, certain improvements are required for the vibratory anchor to be reliable and functional in deep water. A second generation vibratory anchor will be designed that will include improvements in the support guidance system, the fluke shaft linkage, and the battery power unit package. The second generation design will be tested to evaluate the mechanical improvements and to substantiate or modify the analytical procedures used to optimize the anchor.

FUTURE WORK

Plans for the immediate ongoing deep ocean anchoring development are directed to the vibratory anchor concept. Prototypes of the second generation design will be fabricated. Controlled testing of the prototypes in both clay and sand will be conducted to confirm and/or modify the analytical procedures devised for predicting anchor breakout resistances for particular fluke sizes and seafloor sediments with a given vibratory power unit. Other testing with the prototype will be conducted in water 1000 to 6000 feet deep to evaluate the functioning of the anchor at these depths.

Still another phase of the immediate ongoing work will be a model investigation. This study will attempt to establish the effect on the holding capacity of anchors subjected to random variations in loading as imposed by a structure on the sea surface.

It is anticipated that a broadened deep sea anchor development program will follow the vibratory anchor work. A hard seafloor embedment anchor will be developed to provide anchoring capability in seafloor types not suited to the vibratory anchor. An operational depth of 6000 feet, a 50,000-pound holding capacity, and functionability in seafloors ranging from sediments to rock and coral with compressive strengths to 15,000 psi are the goals for the hard seafloor anchor. To increase embedment type anchorage potential to a greater percentage of the seafloor, the vibratory anchor will be modified to be functional at water depths to 20,000 feet. In addition to these efforts, a mooring system utilizing embedment anchors will be developed to provide from 100,000 to 300,000 pounds of holding capacity in water depths to 6000 feet. To achieve these goals, existing embedment anchors and/or new modular types will be studied.

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13. ABSTRACT

Five anchor design concepts have been explored in conjunction with the program to develop an improved deep sea mooring capability. The knowledge gained from study of these anchor concepts, "Free-fall", (2) "Pulse-jet", (3) "Explosive", (4) "Padlock", and (5) "Vibratory" are summarized in this report.

The vibratory anchor is currently the center of the deep sea anchoring development effort. A first generation design has demonstrated the concept to be feasible. Tests have shown that improvements are required for the vibratory anchor. An analytical study has been performed to assist in optimizing a second generation design. Improvements incorporated in the second generation design will be based on information from tests of the first design and the analytical study. The improved design will be tested in a range of seafloor sediment types and water depths to rate its capabilities and establish its reliability.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Underwater vehicles						
Deep ocean vehicles						
Ship anchors						
Free-fall anchors						
Pulse-jet anchors						
Explosive anchors						
Padlock anchors						
Vibratory anchors						

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